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US FAA-STYLE FLAMMABILITY ASSESSMENT OF LITHIUM ION CELLS AND BATTERY PACKS IN AIRCRAFT CARGO HOLDS

(BY: E^{X}PONENT FAILURE ANALYSIS ASSOCIATES)

Exponent®

Failure Analysis Associates

US FAA-Style Flammability Assessment of Lithium Ion Cells and Battery Packs in Aircraft Cargo Holds

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Acronyms and Abbreviations

"	Inches
ALPA	Air Line Pilots Association
DOT	Department of Transportation
Exponent	Exponent Failure Analysis Associates
FAA	Federal Aviation Administration
lbs.	Pounds weight
LH	left hand
RH	right hand
mL	milli-liters
PRBA	Portable Rechargeable Battery Association
RSPA	Research and Special Programs Administration
SOC	State of Charge

Executive Summary

Exponent Failure Analysis Associates (Exponent) constructed a 64-cubic-foot test chamber similar to that described in the Federal Aviation Administration's (FAA) report entitled "Flammability Assessment of Bulk-Packed, Nonrechargeable Lithium Primary Batteries in Transport Category Aircraft" for performing testing on lithium ion (rechargeable or secondary) cells and battery packs. In that chamber, Exponent conducted flame attack tests on single, multiple, and bulk packaged lithium ion cells and battery packs. Exponent has also conducted tests to assess the impact on cargo hold liner material of lithium ion cells and battery packs attacked by fire; and tested the effectiveness of Halon 1301 in suppressing lithium ion cell and battery pack fires. This report describes the results of the Exponent testing.

Based on the testing conducted, Exponent has concluded the following:

1. Direct flame impingement on small, unpackaged quantities of bare cells and battery packs can lead to internal thermal runaway of individual cells and venting of gases. The vent gases are generally ignited by the pre-existing flame, increasing the total heat flux produced by the fire. In a few cases, cells will rupture and eject their contents.
2. Halon 1301 is very effective in controlling burning lithium ion cells.
3. The fires used in the testing program had minimal effects on bulk packaged lithium-ion cells at 50% or less state of charge. Direct flame impingement over a few minutes on bulk packages of cells did not lead to significant venting or involvement of the cells in the fire.
4. The aircraft cargo liner material used in the testing, which is commercially available and which we believe is typical, is capable of withstanding the tested flame impingement from burning gases vented by lithium-ion cells subjected to external heating.

Introduction

At the request of the Portable Rechargeable Battery Association (PRBA), Exponent Failure Analysis Associates (Exponent) conducted tests on lithium ion (secondary or rechargeable) cells and battery packs at both 35% and 50% of full charge. The test setup and procedures are similar to those described in the Federal Aviation Administration's (FAA) report [1] entitled "Flammability Assessment of Bulk-Packed, Nonrechargeable Lithium Primary Batteries in Transport Category Aircraft" (FAA report). In particular, Exponent constructed a 64-cubic-foot test chamber, similar to that described in the FAA report. In that chamber, Exponent conducted flame attack tests on single, multiple, and bulk packaged lithium ion cells and battery packs. Exponent has also conducted tests to assess the impact on cargo hold liner material of lithium ion cells and battery packs attacked by fire; and tested the effectiveness of Halon 1301 in suppressing lithium ion cell and battery pack fires. This report describes the results of the Exponent testing.

Background

On December 15, 2004, the Research and Special Programs Administration (RSPA) of the US Department of Transportation (DOT) issued an interim final rule [2] "imposing a limited prohibition on offering for transportation and transportation of primary (non-rechargeable) lithium batteries and cells as cargo aboard passenger-carrying aircraft and equipment containing or packed with large primary lithium batteries." Per the Federal Register notice, this ban was prompted by four factors:

1. An April 28, 1999 incident at Los Angeles International Airport (LAX) involving pallets of lithium primary cells that had been damaged while being unloaded and subsequently caught fire.
2. An FAA Technical Report on Primary Lithium Batteries [1] concluded that the presence of primary lithium batteries can "significantly increase the severity of an in-flight cargo compartment fire," and that a fire involving lithium primary batteries can not be effectively controlled by release of Halon 1301.
3. Additional incidents involving lithium batteries.
4. A September 29, 2004 petition to RSPA from the Air Line Pilots Association (ALPA) requesting that RSPA develop "packaging standards for lithium primary batteries similar to those in place for other commodities that, in the event of a fire, including a suppressed cargo fire, would result in the loss of an aircraft."

In the Federal Register notice, RSPA also states,

> *FAA and RSPA have similar concerns with* [secondary] *lithium (rechargeable/lithium ion) batteries in that they appear to have similar self-ignition characteristics as primary lithium cells and batteries when subjected to thermal and physical abuse conditions. However, the risks associated with the shipment of secondary (rechargeable/lithium ion) lithium batteries, particularly with respect to their ability to burn in an atmosphere containing Halon, are currently unclear. Studies conducted by the FAA focused only on shipments of primary lithium batteries, not secondary (rechargeable) lithium batteries.*

The FAA Report (referenced in the Federal Register notice by RSPA) describes a series of tests conducted on lithium primary batteries designed to investigate "ignition source intensity, effect of battery quantity, fire propagation between batteries, effect of packing materials, temperature rise in the test chamber, pressure rise in the test chamber, effect of Halon 1301 fire suppression systems, and effect on cargo liner integrity." The majority of FAA's tests were conducted in a 64-cubic-foot test facility where lithium primary batteries or groups of batteries could be suspended above a small 1-propanol pool fire and observed. This chamber would accept segments of cargo hold liner for cargo liner integrity tests. Halon 1301 could be discharged into the chamber for fire suppression tests.

Though focused on lithium primary cells, the FAA Report also describes two fire pan tests conducted on rechargeable laptop computer batteries (unknown state of charge) in a 64-cubic-foot chamber that were considered "out of the scope" of the study. The author notes that the "batteries did not burn with an open flame" and that the measured peak temperatures were not much greater than those measured without batteries present.

In May of 2001, Exponent conducted an analysis [3] of the effects of venting lithium-ion (rechargeable or secondary) cells (due to external fire attack) on the severity of a cargo hold fire. This analysis was based on available information regarding the contents of lithium-ion cells, the composition and characteristics of vent gases from lithium-ion cells, the known effects of Halon 1301, and published literature regarding aircraft cargo hold construction and fires within aircraft cargo holds. In that study, Exponent concluded that "lithium-ion cells or battery packs would be unlikely to vent prior to a cargo hold fire being detected and Halon 1301 being discharged," and that "after Halon is released, the compartment atmosphere is resistant to flame propagation despite the addition of flammable gases such as…vent gases from lithium-ion cells."

In late 2004 and early 2005, at the request of PRBA, Exponent conducted an experimental study of lithium-ion (rechargeable or secondary) cell and battery performance under cargo hold fire conditions. This study was designed to be comparable in scope to the FAA Report on lithium primary batteries. As such, Exponent constructed a 64-cubic-foot chamber, per the description in the FAA Report, and ran tests with groups of bare cells and battery packs. Exponent also ran tests on cells and battery packs in the presence of cargo hold liner specimens, and finally with Halon 1301 addition. This report describes the results of the Exponent experimental study.

Experimental Set-Up

64-Cubic-Foot Test Chamber

A 64-cubic-foot test chamber (Figure 1) was constructed to be as similar as possible to the 64-cubic-foot chamber described in the FAA Report. The Exponent 64-cubic-foot chamber was constructed of $^1/_8$" un-insulated steel sheeting and measured 48" by 48" by 48" on the interior. The walls of the chamber were painted semi-gloss black. The front of the chamber was equipped with a full width and height door that included a 36" by 36" Plexiglas window. The window was sealed to the chamber door with high temperature foil tape.

Two rectangular (12" wide by 6" high) Mylar covered over-pressure vents were centered on the left hand (LH) and right hand (RH) walls, approximately 2" below the ceiling of the chamber. Another small Mylar covered window (3" by 3") for the video camera was centered in the RH wall, approximately 14" below the ceiling of the chamber. Three 1" diameter vents were centered on the LH, back, and RH walls approximately 1½" above the chamber floor.

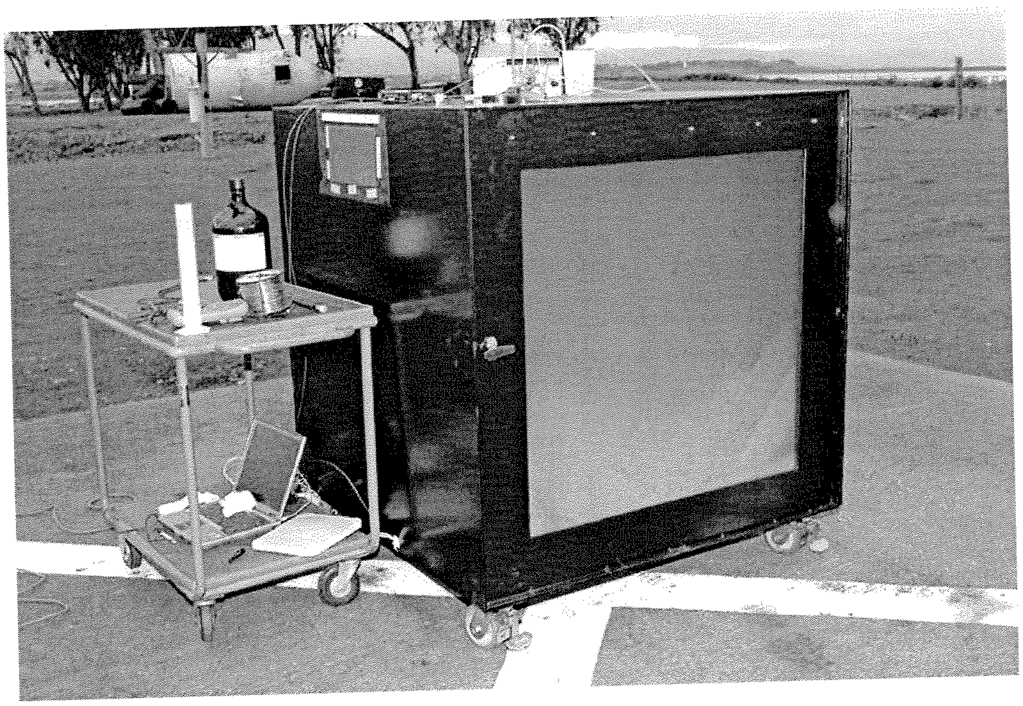


Figure 1. 64-cubic-foot test chamber.

Chamber Instrumentation

The chamber was instrumented with four type-K high temperature fiberglass jacketed thermocouples. They were mounted from a vertical steel rod, and were centrally located inside the chamber at heights of 12", 24", 36", and 48" from the floor. For some tests, an additional thermocouple was taped to the outer surface of one of the lithium ion cells.

The 64-cubic-foot test chamber was also equipped with two circular foil heat flux transducers[1], which were calibrated to a range of 0 to 7.5 BTU/ft^2-sec. See Figure 2 for an example heat flux transducer. Cooling water was circulated through the heat flux transducers during testing. One transducer was mounted in the center of the chamber ceiling Figure 3, and the second transducer was mounted on the RH chamber wall; centered and up 12" from the chamber floor (Figure 4).

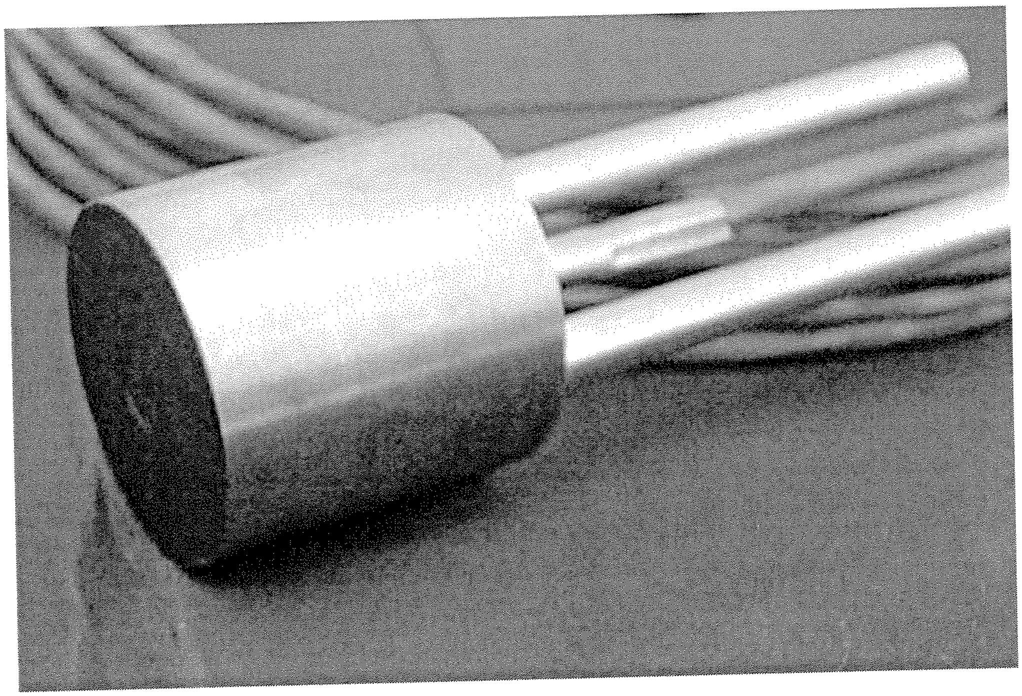


Figure 2. Example Thermogage TG-1000 circular foil heat flux transducer. The actual transducers utilized by Exponent incorporated a flange for mounting.

Thermocouple and heat flux data were recorded with a Personal Daq[2] data acquisition system at a rate of 1 scan per second.

1 Thermogage TG-1000-0 transducers. Serial number 7681 and 7682. Vatell Corporation, P.O. Box 66, Christiansburg, VA 24068.

2 Personal Daq, Model: 56, S/N: 248407. IO Tech, Inc., 25971 Cannon Road, Cleveland, Ohio 44146.

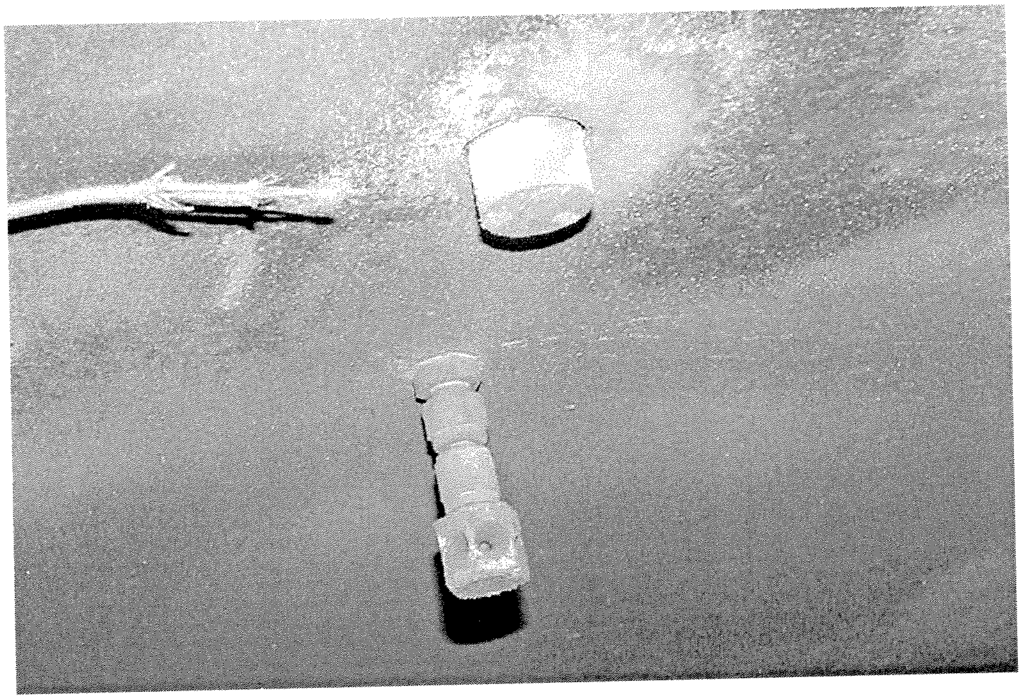


Figure 3. Interior ceiling of 64-cubic-foot chamber. Clockwise from upper left: 48" height thermocouple, upper heat flux transducer, and Halon nozzle.

Ignition Fire Source

One of two different fire sources was used for all tests; either a 5" diameter by 2" high or 11" diameter by 2" high circular aluminum pan. In accordance with the FAA tests, the quantity of 1-Propanol (propanol) fuel used was 50 mL for the 5" pan tests and 220 mL for the 11" pan tests.

All lithium ion cells were positioned above the fire source by placing them on a support grate elevated approximately 4" above the fire pans. The support grate was constructed of an angle iron frame and a steel mesh grid (Figure 4). The cells or battery packs were typically secured to the grid with bailing wire.

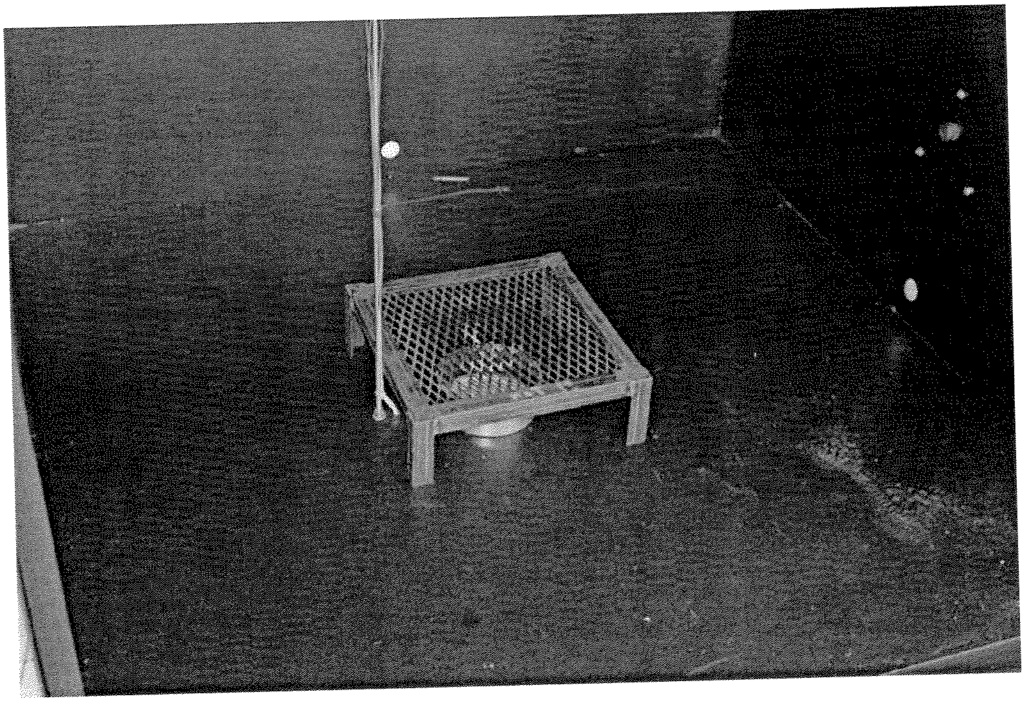


Figure 4. 5" pan under the support grate. Also in view, the 12" thermocouple, two of the three 1" diameter lower vents, and the heat flux transducer on the lower RH wall.

Chamber Baseline Tests

Prior to performing tests with lithium ions cells, the 64-cubic-foot chamber was calibrated with both the 5", and the 11" diameter ignition fire source. Temperature and heat flux data were recorded from all sensors, but only data from the 48" ceiling temperature and the upper heat flux transducer were compared to the baseline data presented in the FAA report. Exponent ran multiple tests while varying the amount of vent area by completely or partially blocking some or all of the three 1" diameter lower vents. Our baseline testing indicated that the 48" ceiling temperatures and upper heat flux replicated the published FAA results with all three 1" vents open. In this configuration, the 5" pan 1-Propanol fire would burn for approximately 3½ to 4 minutes. The 11" pan 1-Propanol fire would burn strongly for approximately 1½ minutes and then the flame would begin to weaken. Note that the temperature and heat release rate data presented in the FAA Report indicates similar performance: a fire burning strongly for approximately 1½ minutes and then weakening.

Halon 1301

Recycled Halon 1301[3] (Halon) was purchased from H3R Inc. of Larkspur California for use in the lithium ion cell tests. All tests were conducted with a pre-metered charge of Halon that was

[3] H3R Inc. provided a certificate of compliance that the Halon 1301 met Mil-B-38741.

dispensed from a 2.25-liter stainless steel charge cylinder. Prior to each Halon test, the empty charge cylinder was placed on a scale, weighed, and filled with 1.4 lbs. of Halon 1301. The charge weight of 1.4 lbs. was determined based on the FAA suggested concentration of 5.5% Halon 1301 in cargo holds. The charge cylinder was then mounted to the exterior of the 64-cubic-foot chamber on the Halon port. The Halon port, centered in the chamber ceiling, consisted of six $^1/_8$" diameter holes arranged in a radial pattern around the fitting (Figure 3).

At a predetermined time during the fire event, Halon was released into the chamber by opening a valve between the Halon charge cylinder and chamber. Halon would typically flow into the chamber for approximately 2½ minutes.

Cargo Hold Liner

A series of tests were conducted to determine the effect of fire with lithium ion cells and batteries on standard aircraft cargo liner material. The tests were conducted in the 64-cubic-foot chamber using the 5" pan and 50 ml of 1-Propanol.

Two styles of cargo liner material, both 0.030" in thickness were purchased from M.C. Gill Corporation of El Monte, California: 1066 Laminate and 1367A Laminate. The M.C. Gill website [4] describes these materials as follows:

Gilliner 1066 Laminate	*Woven fiberglass cloth reinforced polyester, general purpose cargo liner. M.C. Gill proprietary product.*
Gillfab 1367A Laminate	*Woven fiberglass cloth reinforced phenolic, high impact resistant, low smoke and toxicity cargo liner with white Tedlar® on the face side. Qualified to Boeing specification BMS 8-223 Cl 2 Gr B Types 13 thru 40, McDonnell Douglas DMS 2419 Cl 1 (Ty 13-40), and Airbus 2550 M1M 000800.*

Copies of the product data sheets for both styles can be found in Appendix A.

For cargo hold liner tests, a 24" high by 24" wide piece of liner material was placed to stand in a semi-circle around the fire pan. The cells were arranged above the fire pan so that some of the positive and some of the negative ends were facing the liner (Figure 5).

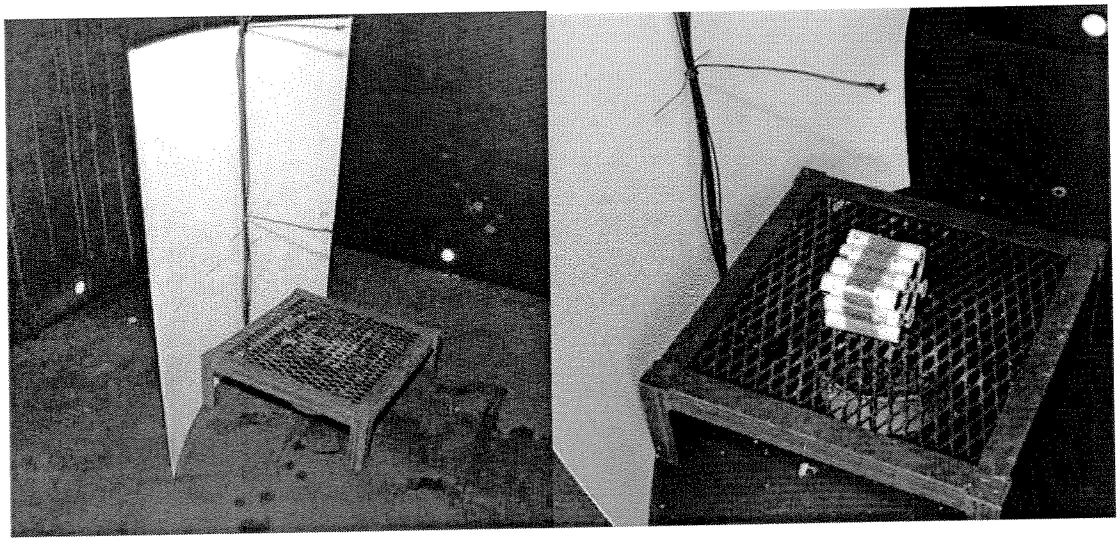


Figure 5. Typical set-up for cargo-hold liner testing.

Cells and Battery Packs

Testing was conducted on lithium-ion cells and packs provided by three manufacturers, designated as A, B, and C. The cells in all tests were cylindrical 18650 model cells. The 18650 designation is a standard industry description indicating that the cell has a diameter of 18 mm, and a length of 650 mm. At present, the 18650 cell is the largest cylindrical cell commonly used in laptop computer battery packs. It is also the cell with the highest capacity of any shape of lithium-ion cell commonly used in laptop computer battery packs. Typical capacities for 18650 cells used in laptop battery packs range from 2.0 to 2.4 Amp hours. Tests were conducted either at as-shipped SOC or at 50% SOC with cells of 2.2 Amp hour capacities.[4] Note that throughout this report, the cell shrink-wrap color has been adjusted to maintain confidentiality.

Battery packs from one manufacturer were tested. These packs each contained eight 18650 lithium-ion cells.

Table 1 Tested lithium-ion cell and battery pack styles

Manufacturer	Cell Style	Configuration Tested	Test SOC	Average Test Voltage
Manufacturer A	18650 (cylindrical)	Cells (bare and bulk packaged)	35% 50%	3.79 3.82
Manufacturer B	18650 (cylindrical)	Cells (bare and bulk packaged)	50%	3.82
Manufacturer C	18650 (cylindrical)	Cells (bare) & Laptop-style packs	50%	3.82

4 Published cell capacities are nominal capacities for a typical cell model. Individual cell capacities may vary slightly from the nominal value. The 50% SOC description is based on the voltage of an average cell with 50% of its capacity remaining.

Results

Lithium ion 18650 cells and battery packs containing 18650 cells from three different manufacturers were tested in the 64-cubic-foot chamber. Tests were conducted on individual bare cells and groups of bare cells, battery packs, cells in bulk shipment packaging, cells where Halon 1301 was added late in the test, and cells and packs placed near aircraft cargo liner material. In addition, calibration tests were run with both 5" and 11" fire pans. For comparison purposes, a test was run with empty bulk shipment packaging, and a test was run with a common box of facial tissue. Table 2 summarizes the completed tests, while data plots from each test can be found in Appendix B. Detailed discussion of the results of each type of test follows.

Figure 6 through Figure 8 summarize data from all of the tests conducted. Figure 6 shows the measured peak ceiling temperatures from all tests conducted as a function of the number of cells involved in each test. This figure shows that peak ceiling temperatures for most of the tests stayed within the range of peak temperatures measured for the 5" and 11" fire pans alone (calibration tests). Peak ceiling temperature did exceed the range of those produced by the 11" fire pan alone in tests of 50, 60, and 150 cells in bulk shipment packaging. However, it is important to note that no cells vented in these tests, so the energy released in these tests was from the 11" fire pan and the burning packaging material only.

Figure 7 shows the peak 5-second average of the heat flux measured at the ceiling of the chamber: the highest value measured for bare cells was 2.0 BTU/ft^2 sec.

Figure 8 shows the peak temperature measured approximately 12" above the chamber floor. All results except for the 150 cells in packaging test[5] cluster in the range of 1000-1400 F. These temperatures are consistent with those produced by burning normal combustibles such as packaging materials.

[5] The box arrangement in this test may have affected the reading at 12".

Table 2. Summary of completed testing

Manf.	Cell Style & Test Configuration	Cell SOC	Cells Tested	Pan Size (in)	Peak Ceiling Temp. (F)	5-second-Average Heat Flux Peak (BTU/ft^2-sec)
A	18650 cells	35%	1	5	325	0.50
			4	5	420	0.80
		50%	2	5	393	0.69
			4	5	432	0.79
			8	5	484	1.03
			16	5	423	1.11
	18650 cells in original packaging	35%	20	5	307	0.59
		50%	60	11	851*	2.10
	18650 cells Halon application late in test	35%	4	5	334	0.81
			16	5	422	1.02
		50%	4	5	451	1.02
			16	5	494	1.22
			32	5	427	1.10
	18650 cells cargo hold liner test	50%	12	5	397	0.91
			12	5	438	0.93
B	18650 cells	50%	1	5	342	0.71
			2	5	372	0.57
			4	5	489	0.83
			8	5	606	1.65
			16	5	592	1.84
	18650 cells in original packaging	50%	50	11	762*	1.99
			150	11	570	1.21
	18650 cells Halon application late in test	50%	4	5	397	0.69
			8	5	426	0.91
			16	5	540	1.99
			32	5	497	1.19
	18650 cells cargo hold liner tests	50%	12	5	514	1.21
			12	5	500	1.22

* Note that none of the cells in this test vented. The results are based on the 1-propanol pan fire and packaging burning only.

Manf.	Cell Style & Test Configuration	Cell SOC	Cells Tested	Pan Size (in)	Peak Ceiling Temp. (F)	5-second-Average Heat Flux Peak (BTU/ft^2-sec)
C	18650 cells	50%	4	5	302	0.51
	18650 packs	50%	8	5	352	0.52
			24	11	319	0.46
	18650 cells Halon application late in test	50%	4	5	301	0.52
	18650 pack Halon application late in test	50%	8	5	307	0.50
	18650 pack cargo hold liner tests	50%	8	5	316	0.57
			8	5	286	0.49
	Empty battery box	n/a	n/a	n/a	392	0.69
	Common Box of Facial Tissues	n/a	n/a	n/a	344	0.61
	5" Calibration			5	282	0.35
	5" Calibration			5	276	0.44
	5" Cal 0% vent			5	253	0.34
	5" Cal 50% vent			5	252	0.43
	5" Cal 100% vent			5	252	0.39
	11" Cal 0% vent			11	593	1.15
	11" Cal 50% vent			11	577	1.36
	11" Cal 100% vent			11	575	1.27

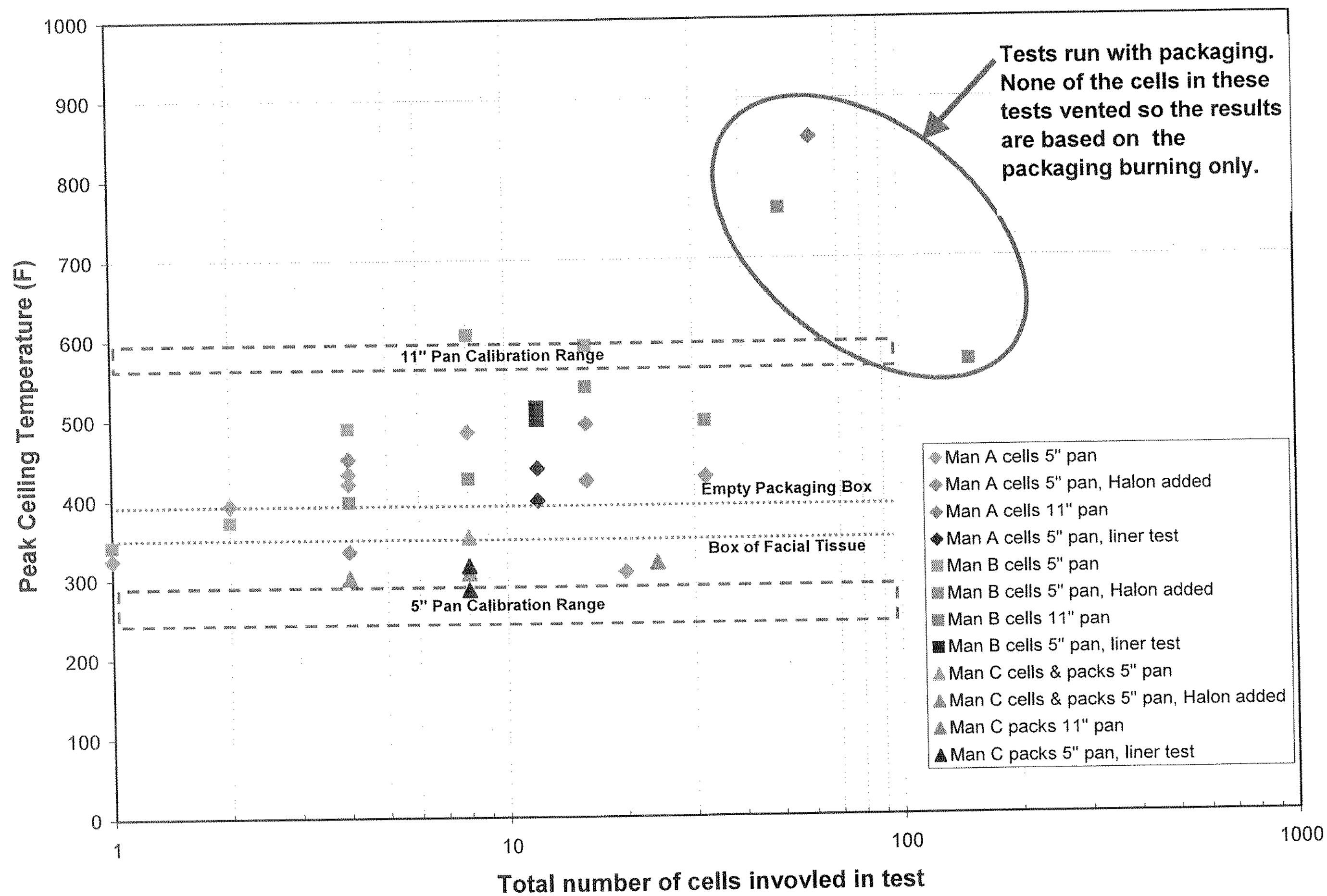


Figure 6. Summary of peak ceiling temperatures for all tests conducted.

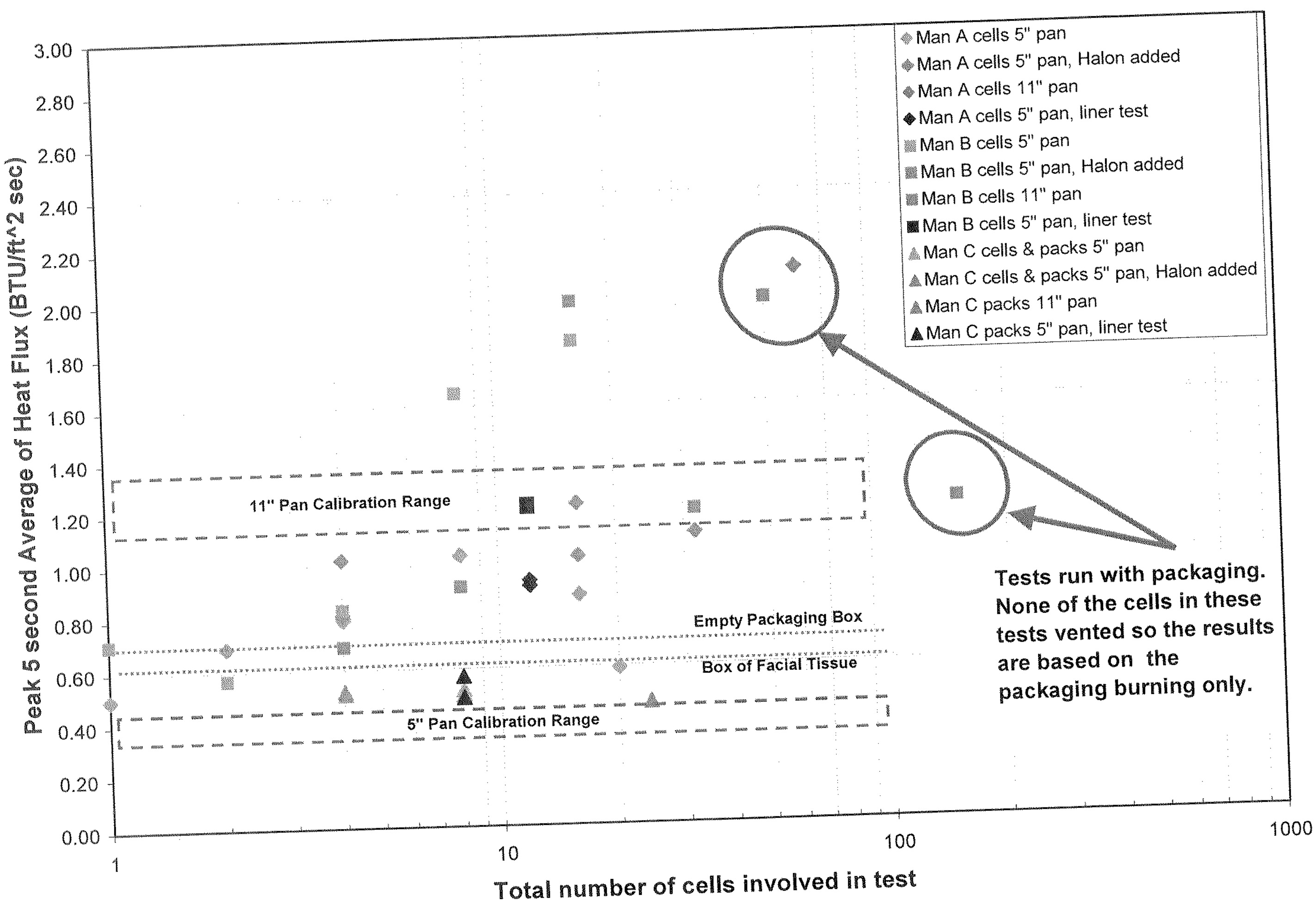


Figure 7. Summary of peak 5-second averaged heat flux at the ceiling for all tests conducted.

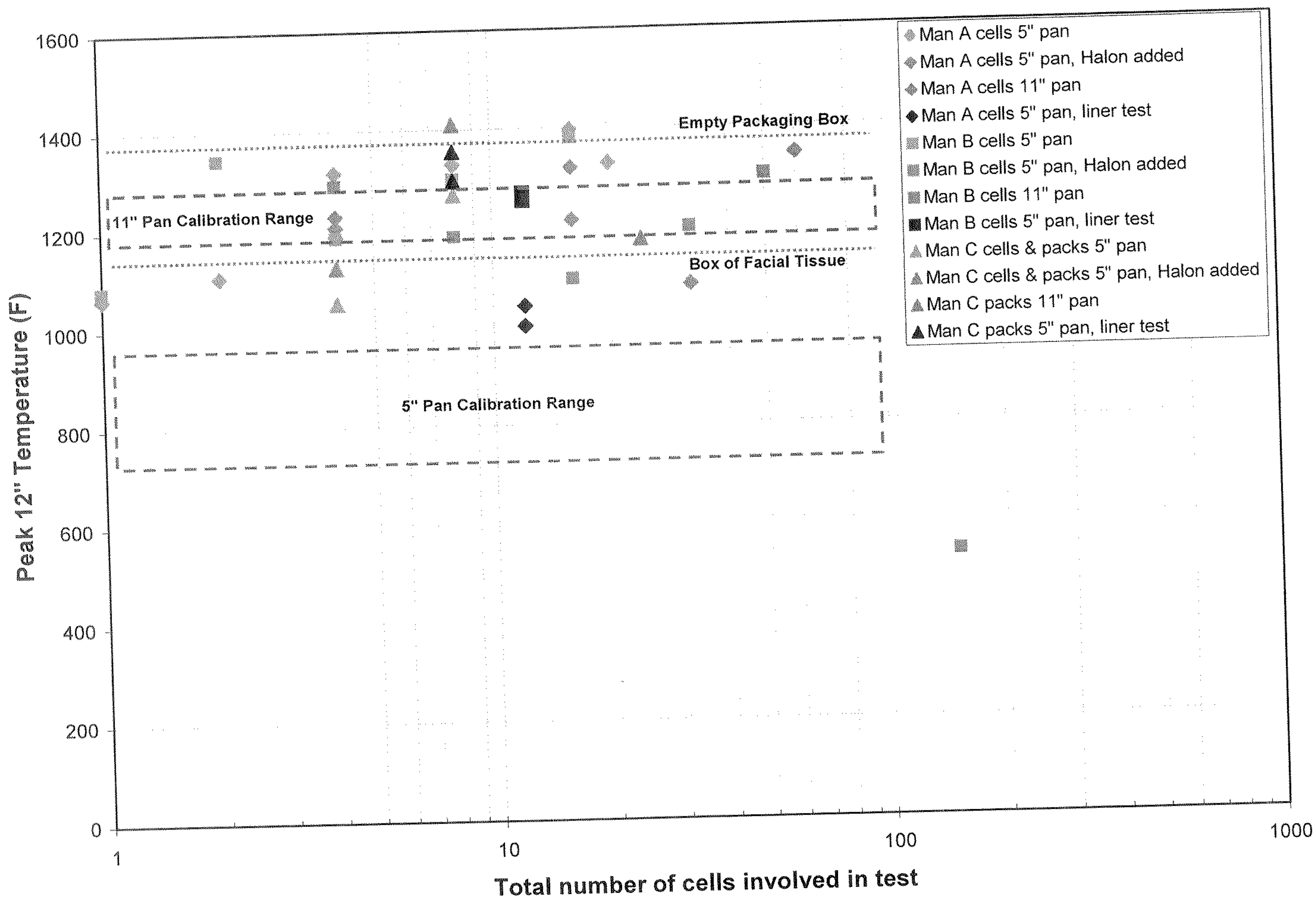


Figure 8. Summary of peak temperatures measured 12 inches above the floor of the chamber.

Cell Tests

Individual 18650 Cell Tests: Manufacturers A, B, and C

A series of tests were conducted on bare 18650 cells not electrically connected in any way, though the cells were often taped together to allow stacking on the test grate to ensure that all of the cells would be exposed to the flames from the pan below (Figure 9). Single and multiple cell combinations from three different manufacturers were tested. A summary of the cells tested in this way can be found in Table 3.

In each test, all of the cells vented electrolyte and lost their external shrink-wrap (Figure 10). In many cases, the cell separator and carbon active material were also likely consumed. The resulting weight loss was approximately 7 to 10 grams. A typical test proceeded as follows: the propanol was ignited, and flames impinged upon, and often surrounded, the test sample. After 1 to 2 minutes, there was a series of audible clicks coinciding with small puffs of flames from the cells. These clicks and puffs were indications of preliminary vent releases, likely resulting from activation of cell charge interrupt devices. After approximately a 1-minute delay, the main cell vents began to open, releasing jets of flammable vapor (electrolyte and plastic decomposition products) and producing a hissing sound. The vapors were ignited by the burning propanol and resulted in jetting flames emanating from the cells for times on the order of a few seconds. In a few tests, some cells then ruptured their cases and expelled their contents.

Figure 11 shows all of the ceiling and 12" temperature measurement data overlaid for this series of tests. It is evident that the ceiling temperature measurements generally fall within a fairly narrow band. The maximum measured ceiling temperature for these tests was 581 °F. The 12" temperature measurements are more variable, reflecting the thermocouple proximity to flames. The maximum measured temperature at 12" above the floor was 1390 °F.

Table 3. Summary of individual 18650 cell tests

Manf.	Cell Style & Test Configuration	Cell SOC	Cells Tested	Pan Size (in)	Peak Ceiling Temp. (F)	5-second-Average Heat Flux Peak (BTU/ft^2-sec)
A	18650 cells	35%	1	5	325	0.50
			4	5	420	0.80
		50%	2	5	393	0.69
			4	5	432	0.79
			8	5	484	1.03
			16	5	423	1.11
B	18650 cells	50%	1	5	342	0.71
			2	5	372	0.57
			4	5	489	0.83
			8	5	606	1.65
			16	5	592	1.84
C	18650 cells	50%	4	5	302	0.51

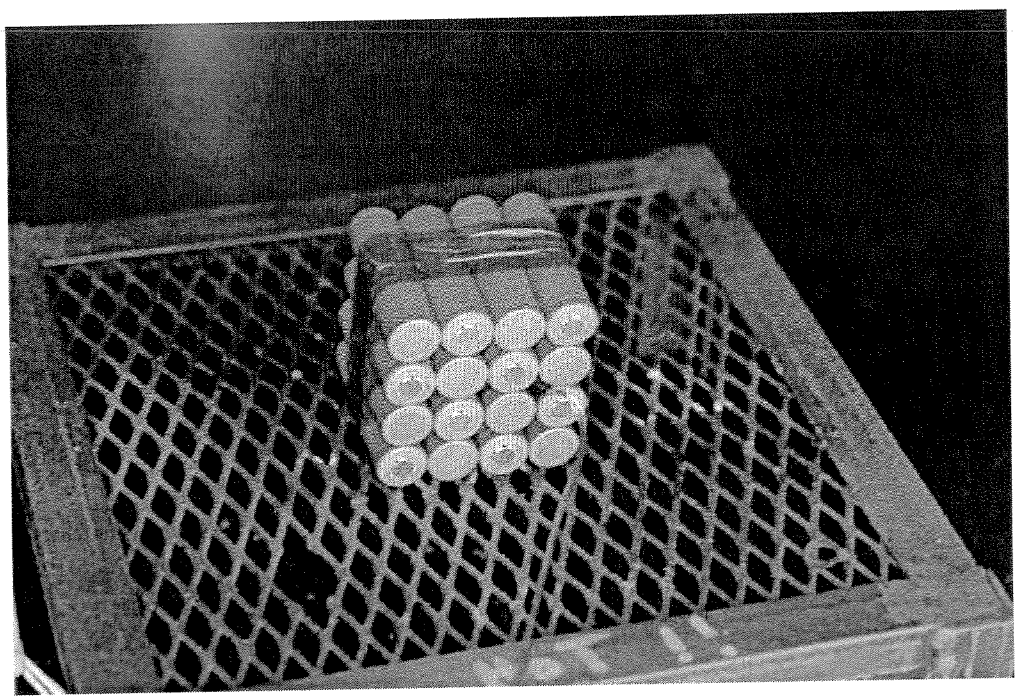


Figure 9. A stack of 16 cells as prepared for testing.

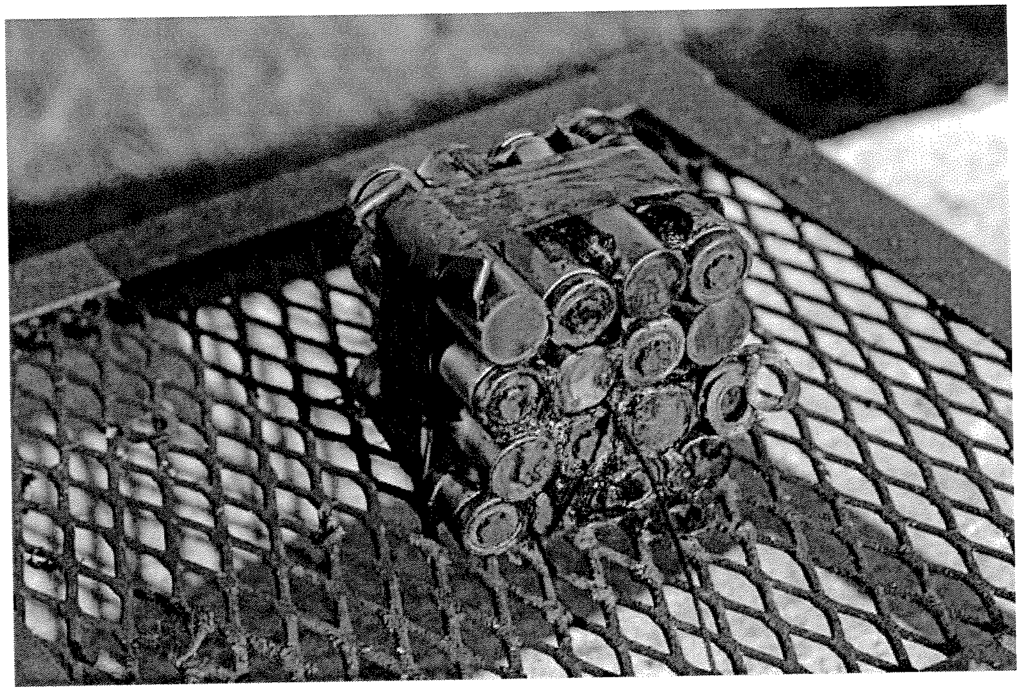


Figure 10. A stack of 16 cells after testing.

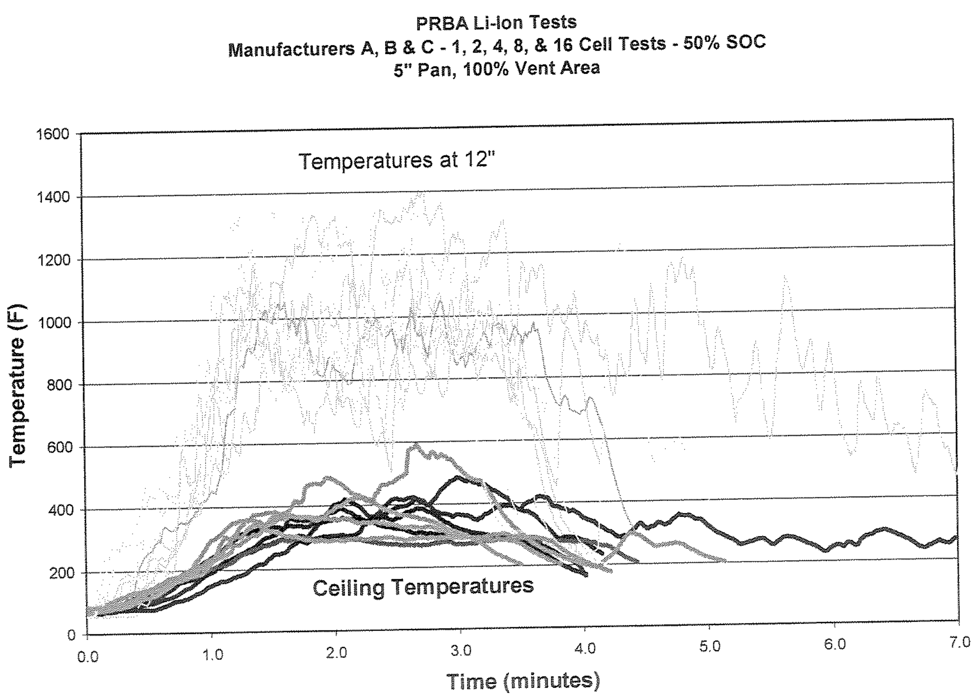


Figure 11. Compilation of temperature data for all bare cell tests.

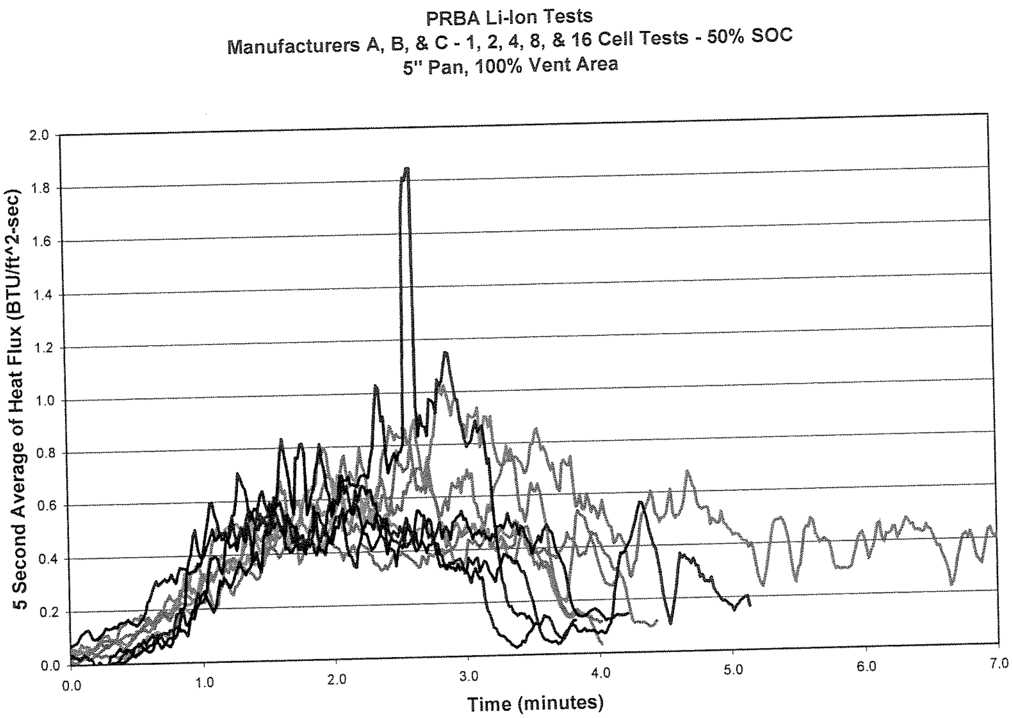


Figure 12. Compilation of 5-second averaged heat flux at the ceiling for all bare cell tests.

Tests of 18650 Cells as Packaged for Bulk Shipment: Manufacturers A & B

A series of tests were conducted on 18650 cells as packaged for bulk shipment. Different manufacturers package their cells slightly differently, so in each test the original manufacturer's packaging was used (Figure 13 through Figure 16). For Manufacturer A, one box contained 20 cells; tests were run with one box (20 cells), and three boxes (60 cells). For Manufacturer B, one box contained 50 cells; tests were run with one box (50 cells) and three boxes (150 cells). The cells were not electrically connected in any way. Since the quantities of cells tested in this way were large, in many tests, the larger 11" pan was used instead of the 5" pan. A summary of the cells tested in this way can be found in Table 4.

None of the cells tested with the manufacturer supplied bulk shipment packaging material vented during the tests. The packaging material itself was generally charred and partially consumed by flames from the fire pan, but always self extinguished when the propanol flame extinguished. All of the cells remained intact (Figure 17 through Figure 20). High heat fluxes measured at the chamber ceiling (up to 2.10 BTU/ft^2 sec) were achieved, but they were due to burning packaging such as cardboard. This testing suggests that a small, short-lived fire may have minimal effect on bulk packaged lithium-ion cells at 50% (or lower) SOC.

Table 4. Summary of tests of 18650 cells as packaged for bulk shipment

Manf.	Cell Style & Test Configuration	Cell SOC	Number of Cells Tested	Pan Size (in)	Peak Ceiling Temp. (F)	5-second-Average Heat Flux Peak (BTU/ft^2-sec))
A	18650 cells in original packaging	35%	20	5	307	0.59
		50%	60	11	851	2.10
B	18650 cells in original packaging	50%	50	11	762	1.99
			150	11	570	1.21

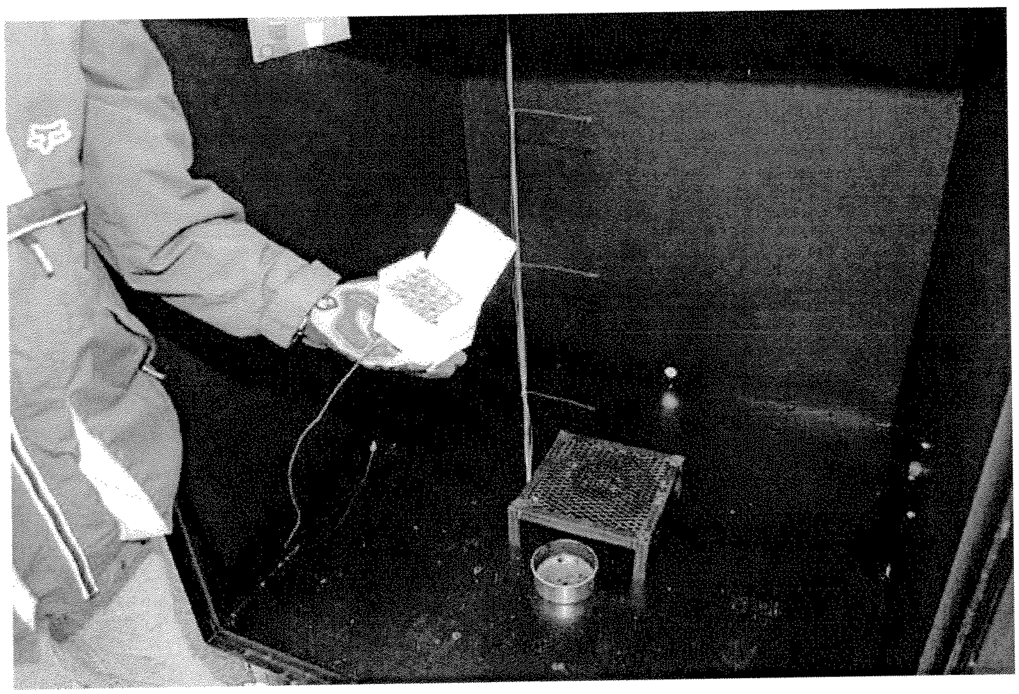


Figure 13. One box of Manufacturer A cells before testing.

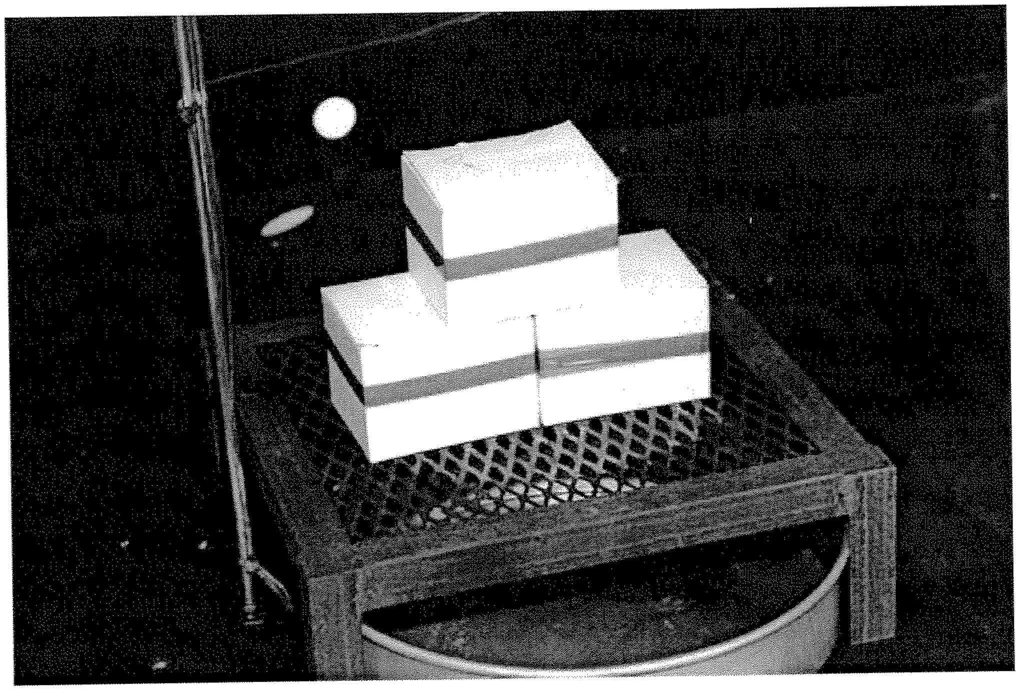


Figure 14. Three boxes of Manufacturer A cells before testing. Note 11" fire pan.

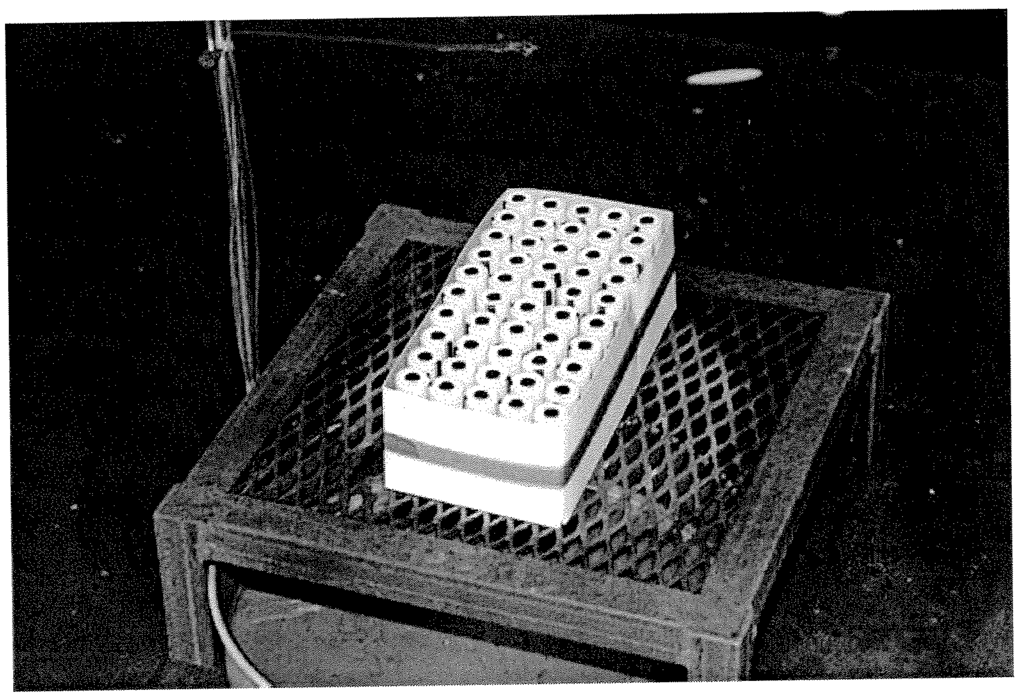


Figure 15. One box of Manufacturer B cells before testing. Note 11" fire pan.

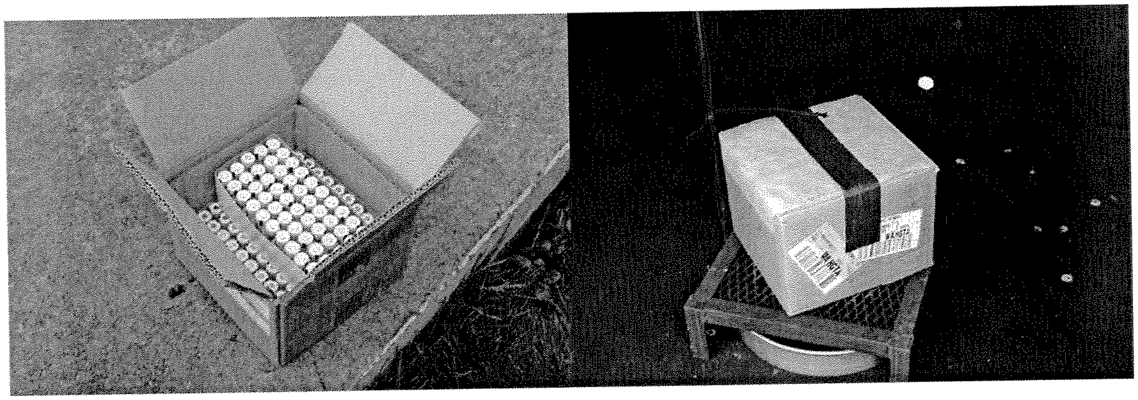


Figure 16. Three boxes of Manufacturer B cells before testing.

Figure 17. One box of Manufacturer A cells after testing.

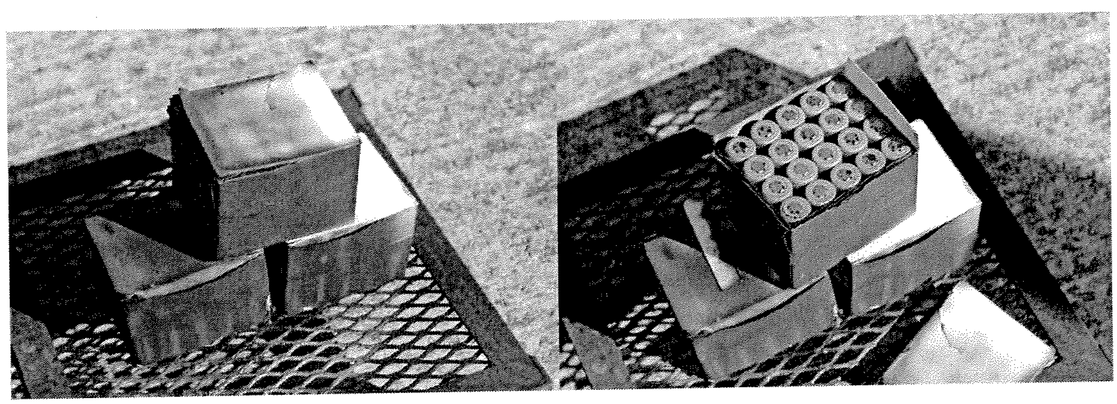


Figure 18. Three boxes of Manufacturer A cells after testing.

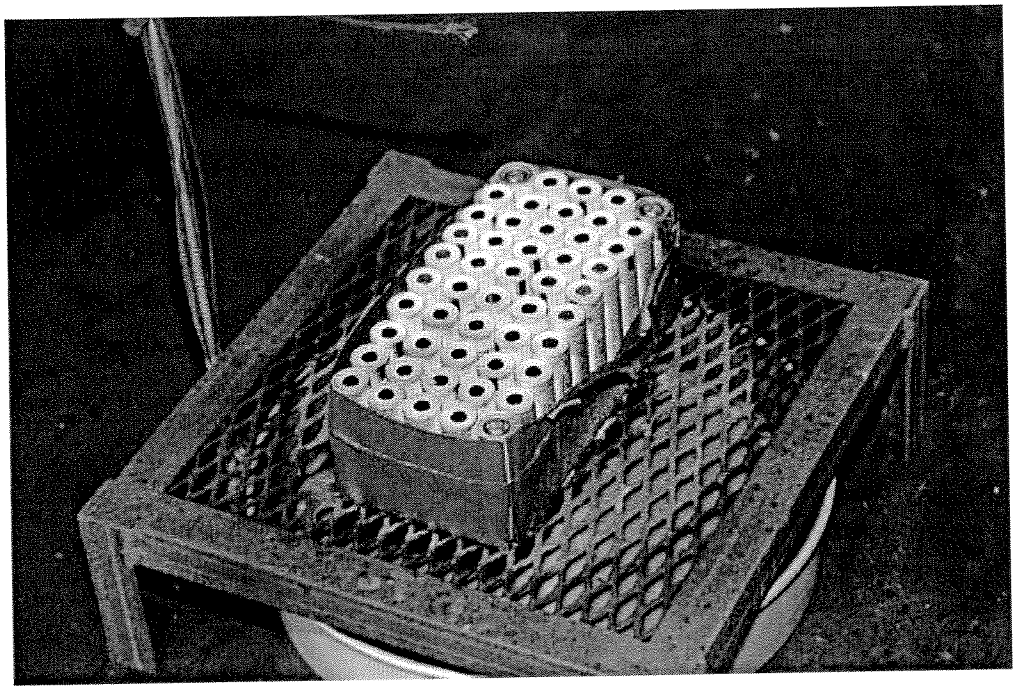


Figure 19. One box of Manufacturer B cells after testing.

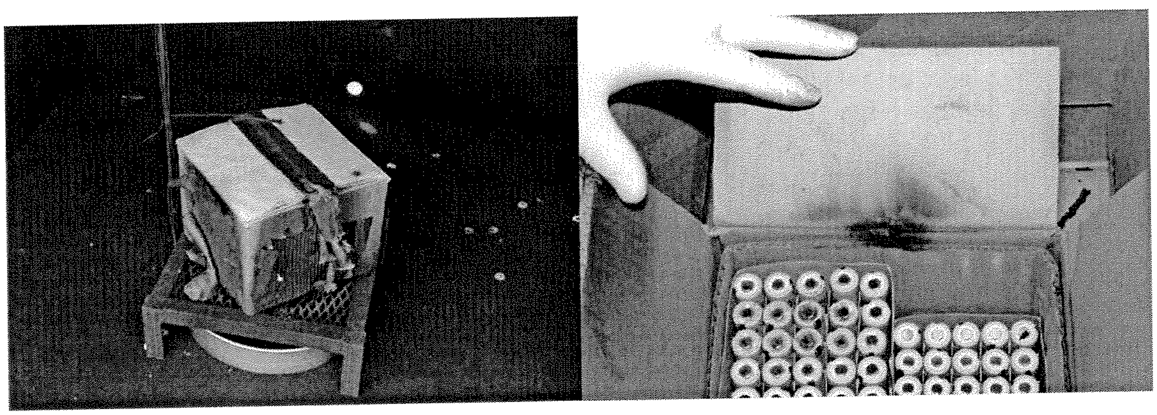


Figure 20. Three boxes of Manufacturer B cells after testing.

Laptop Battery Pack Tests: Manufacturer C

Tests were conducted on laptop battery packs that contain 18650 cells. A summary of the cells tested in this way can be found in Table 5. In the first test, a single pack containing eight cells was tested. In this test, the pack plastic began to be consumed by the propanol flame. Eventually, the cells began to vent with flames. Ultimately, some of the cells ruptured, ejecting and dispersing their contents.

In the second test, three 8-cell packs (total of 24 cells) were stacked together. In order to provide sufficient flame contact area, the 11" pan was used. In this test, the propanol flame began to consume the pack plastic. However, once the propanol flame extinguished, the plastic also stopped burning. Ultimately no cells vented. As a result, peak ceiling temperatures and average heat flux were lower for the 3-pack test than for the single pack test.

Table 5. Summary of laptop battery pack tests

Manf.	Cell Style & Test Configuration	Cell SOC	Number of Cells Tested	Pan Size (in)	Peak Ceiling Temp. (F)	5-second-Average Heat Flux Peak (BTU/ft^2-sec)
	18650 packs	50%	8	5	352	0.52
			24	11	319	0.46

Cargo Liner Integrity Tests: Manufacturers A, B, & C

A series of tests were conducted with bare 18650 cells and computer laptop battery packs in close proximity to samples of aircraft cargo hold liner. A summary of the cells and packs tested in this way can be found in Table 6. The bare cells were not electrically connected, but were taped together so that they could be arranged on the test grate. The cells were positioned so that jetting flames from venting cells would impinge upon the cargo liner materials. Tests of each manufacturer's cells or packs were conducted twice: once with each style of cargo hold liner material.

No test caused ignition or burn through of either cargo hold liner material. Generally, soot deposits on the front face of the cargo liner were observed after testing, and some blistering was observed on the corresponding reverse side of the panel (Figure 21 through Figure 24). In one case, the front face coating of the liner was consumed in one spot; however, the remaining layers of the liner were not consumed and the liner retained its integrity (Figure 25). This testing shows that the tested aircraft cargo liner material, which is commercially available, and believed to be typical, is capable of withstanding the tested flame impingement from burning gases vented by lithium-ion cells subjected to external heating.

Table 6. Summary of cargo liner integrity tests

Manf.	Cell Style & Test Configuration	Cell SOC	Number of Cells Tested	Pan Size (in)	Peak Ceiling Temp. (F)	5-second-Average Heat Flux Peak (BTU/ft^2-sec)
A	18650 cells cargo hold liner test	50%	12	5	397	0.91
			12	5	438	0.93
B	18650 cells cargo hold liner tests	50%	12	5	514	1.21
			12	5	500	1.22
C	18650 pack cargo hold liner tests	50%	8	5	316	0.57
			8	5	286	0.49

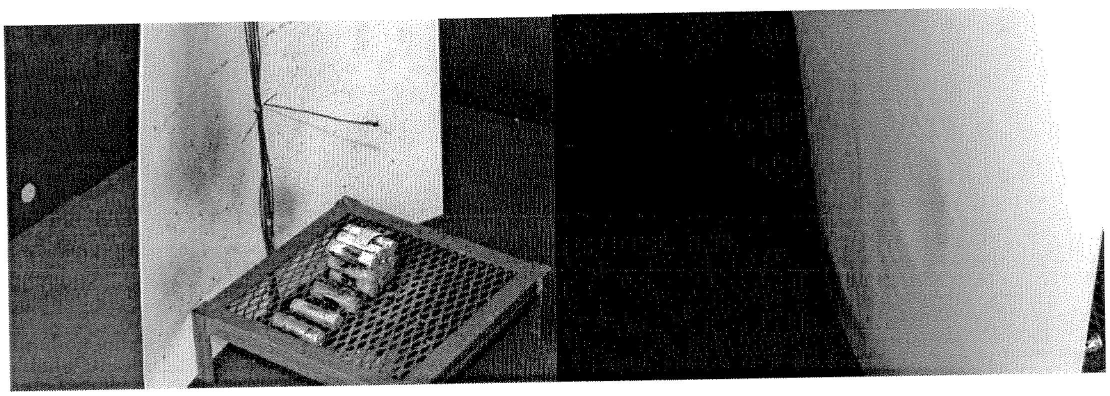


Figure 21. Front and back of Cargo Liner A after testing with 12 Manufacturer A cells.

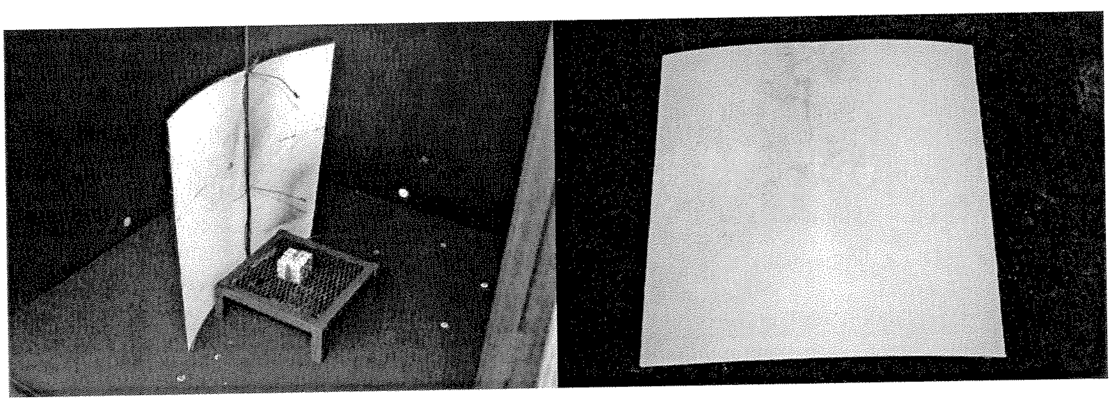


Figure 22. Front and back of Cargo Liner A after testing with 12 Manufacturer B cells.

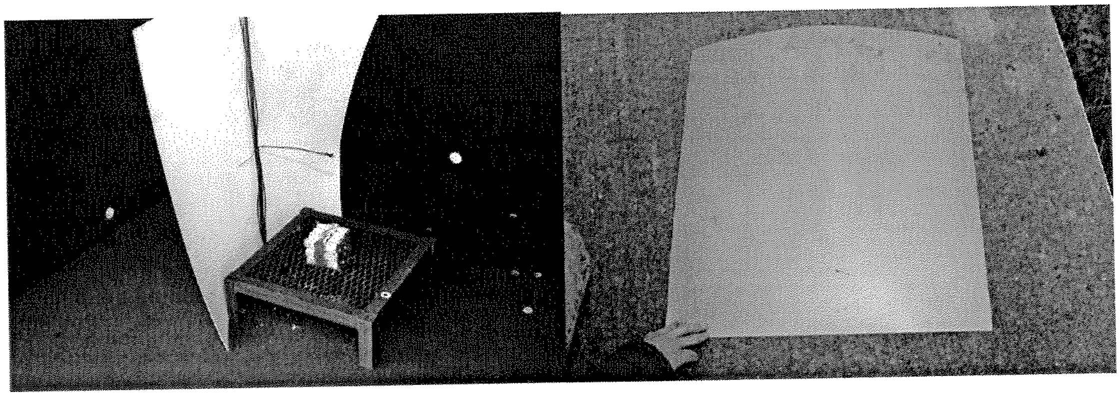


Figure 23. Front and back of Cargo Liner B after testing with 12 Manufacturer B cells.

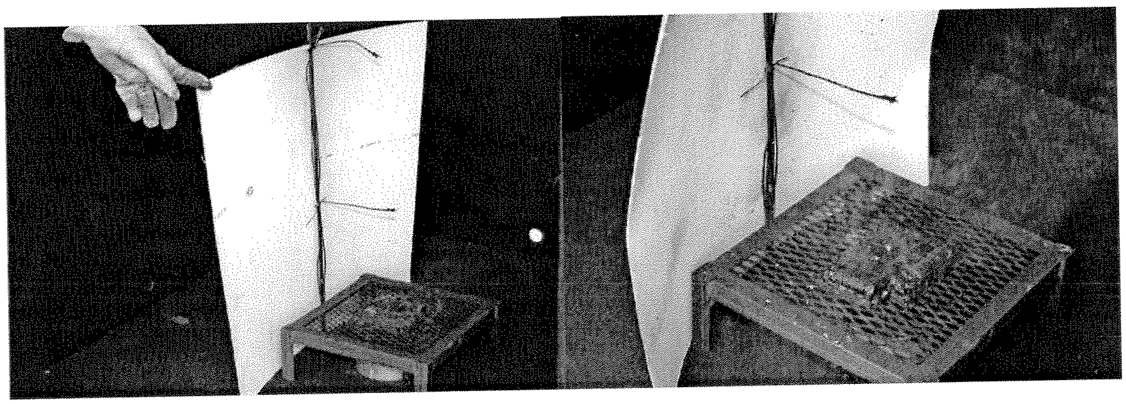


Figure 24. Cargo Liners A & B after testing with Manufacture C battery packs.

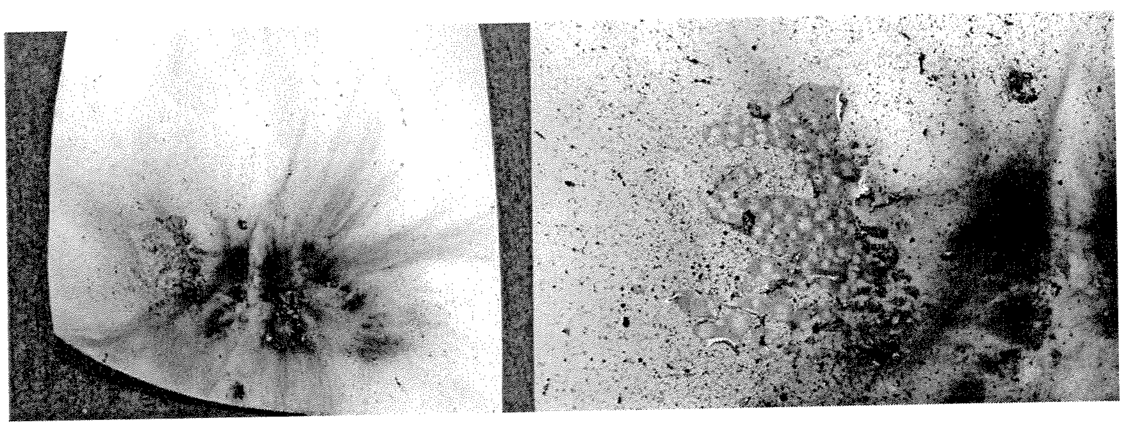


Figure 25. Cargo Liner B after testing with 12 Manufacturer A cells.

Halon 1301 Suppression Tests: Manufacturers A, B, & C

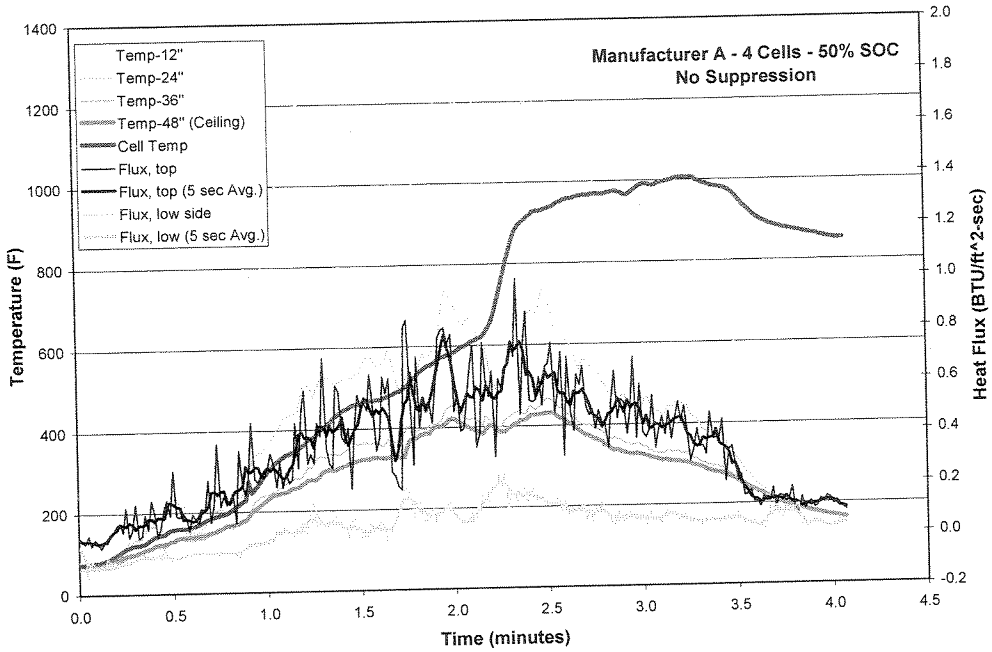
A series of Halon 1301 suppression tests were conducted with bare 18650 cells and computer laptop battery packs. The bare cells were not electrically connected, but were taped together so that they could be arranged on the test grate. A summary of the cells tested in this way can be found in Table 7.

Halon 1301 was applied late in each test, once cells had begun to vent with burning jets. Within seconds of application, all flames were extinguished and no additional flaming was observed for the continuing duration of the test. When Halon 1301 was applied there was a precipitous drop in the chamber temperatures and heat flux measurements. This was entirely consistent with flame suppression. Chamber temperatures and heat fluxes remained low for the duration of the testing. Note that Halon 1301 application did not cool the cells (Figure 26). Thermal runaway of individual cells and cell venting continued to occur after Halon 1301 was applied. Examination of all cells from Exponent's Halon 1301 tests showed that they had vented. However, with Halon 1301 present, this process did not result in flaming combustion.

When the data taken during Halon 1301 suppression tests is compared to data from similar tests where suppression was not used, the effect of Halon 1301 is evident (Figure 26 through Figure 30). Halon 1301 application effectively suppresses the fire.

Table 7. Summary of Halon 1301 suppression tests

Manf.	Cell Style & Test Configuration	Cell SOC	Number of Cells Tested	Pan Size (in)	Peak Ceiling Temp. (F)	5-second-Average Heat Flux Peak (BTU/ft^2-sec)
A	18650 cells Halon application late in test	35%	4	5	334	0.81
			16	5	422	1.02
		50%	4	5	451	1.02
			16	5	494	1.22
			32	5	427	1.10
B	18650 cells Halon application late in test	50%	4	5	397	0.69
			8	5	426	0.91
			16	5	540	1.99
			32	5	497	1.19
C	18650 cells Halon application late in test	50%	4	5	301	0.52
	18650 pack Halon application late in test	50%	8	5	307	0.50



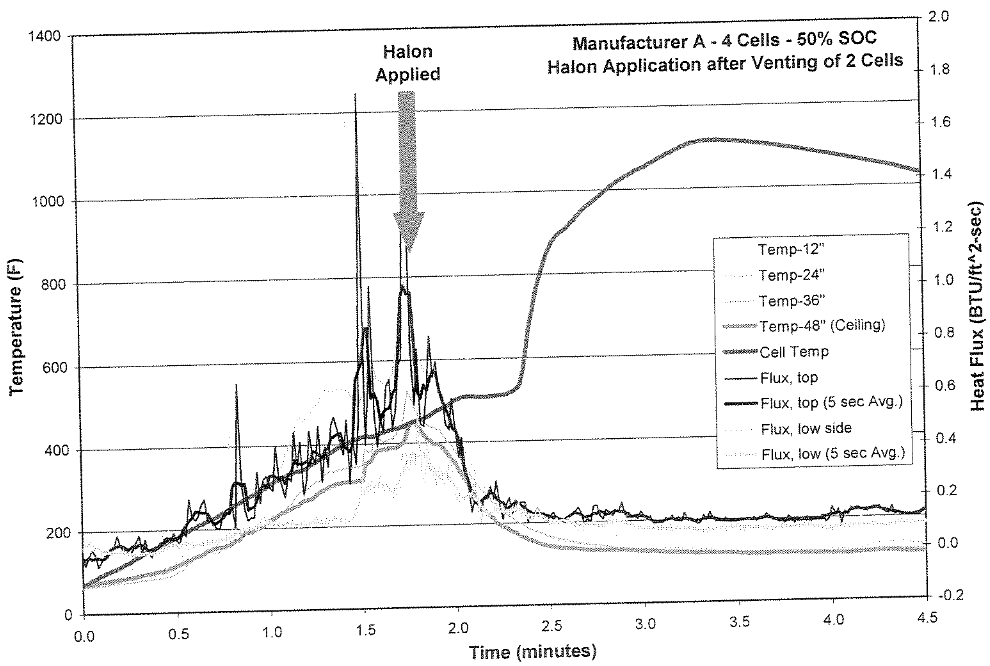
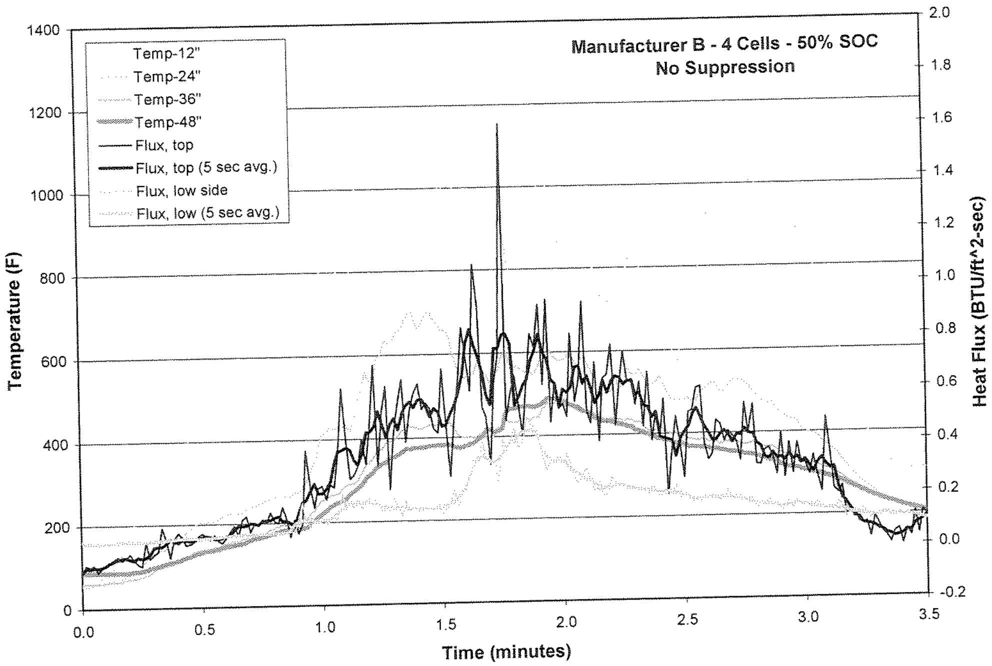


Figure 26. Tests with 4 Manufacturer A cells, without suppression (top), and with Halon 1301 application after cells began to vent (bottom).



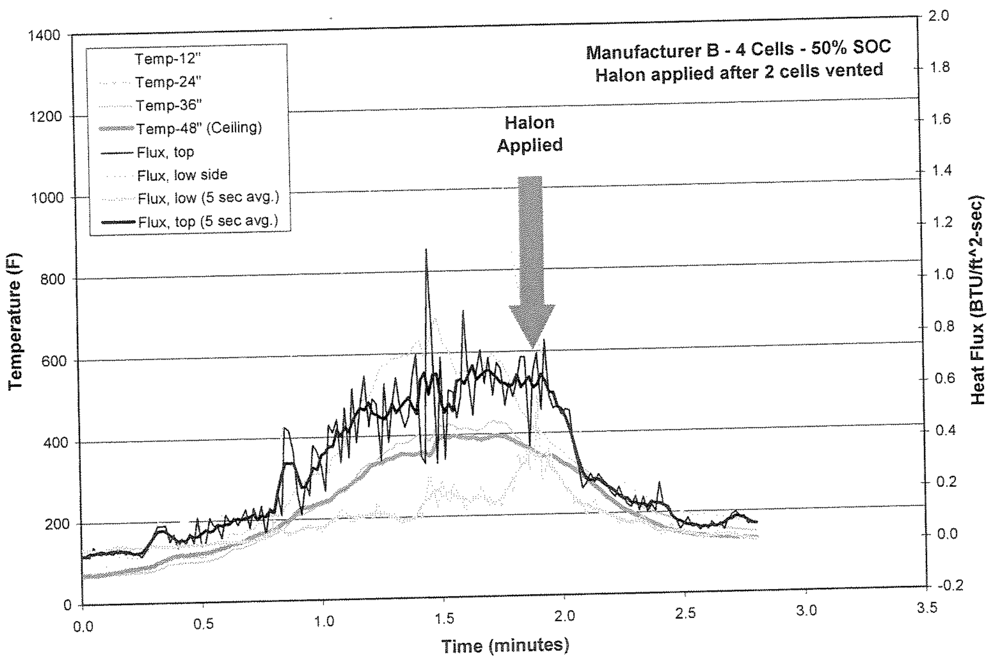
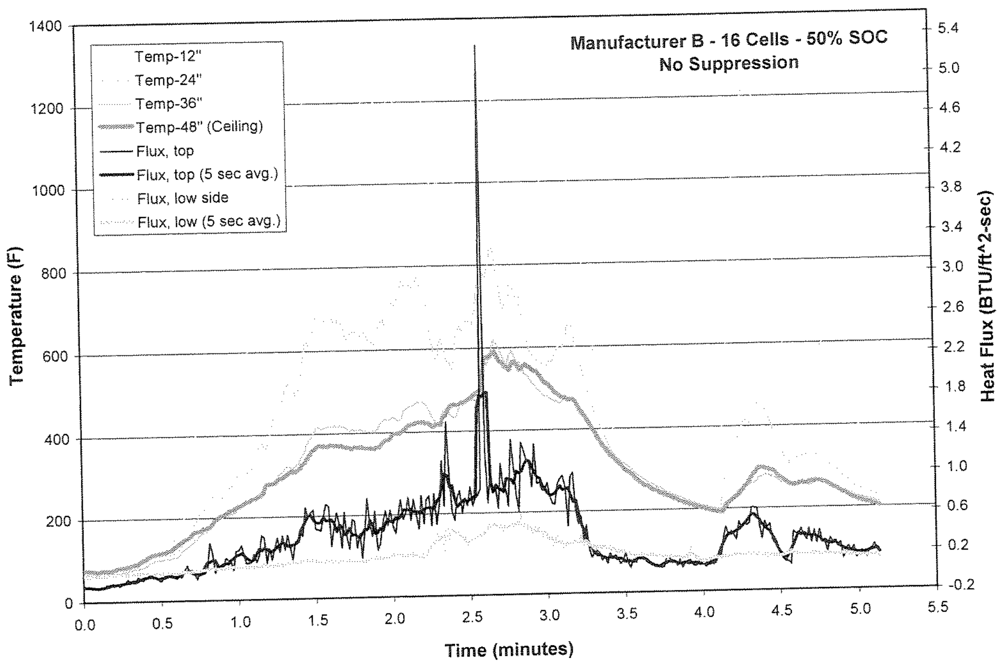


Figure 27. Tests with 4 Manufacturer B cells, without suppression (top), and with Halon 1301 application after cells began to vent (bottom).



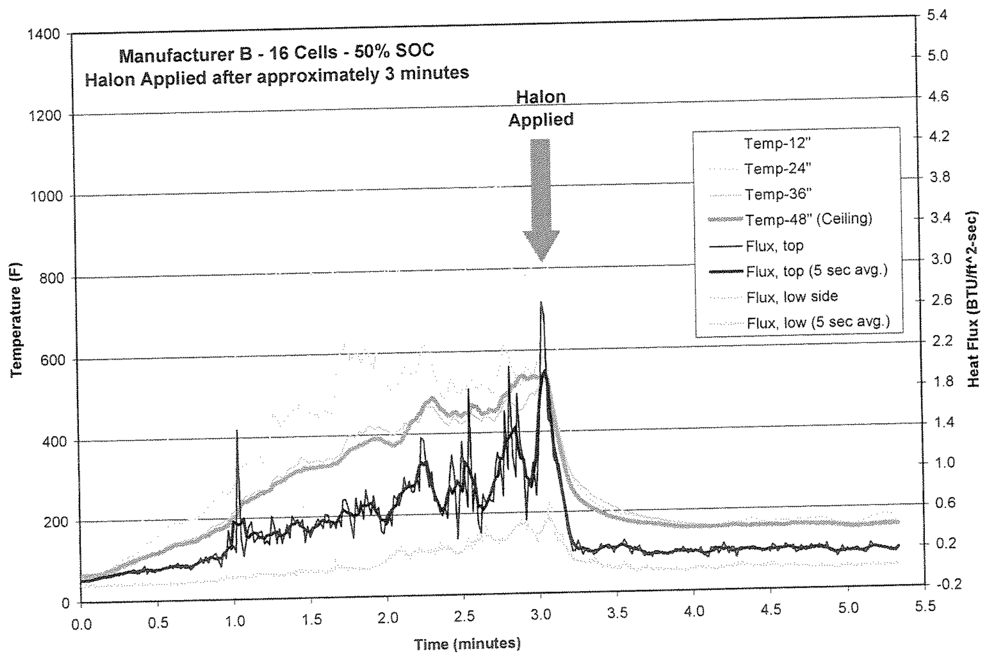
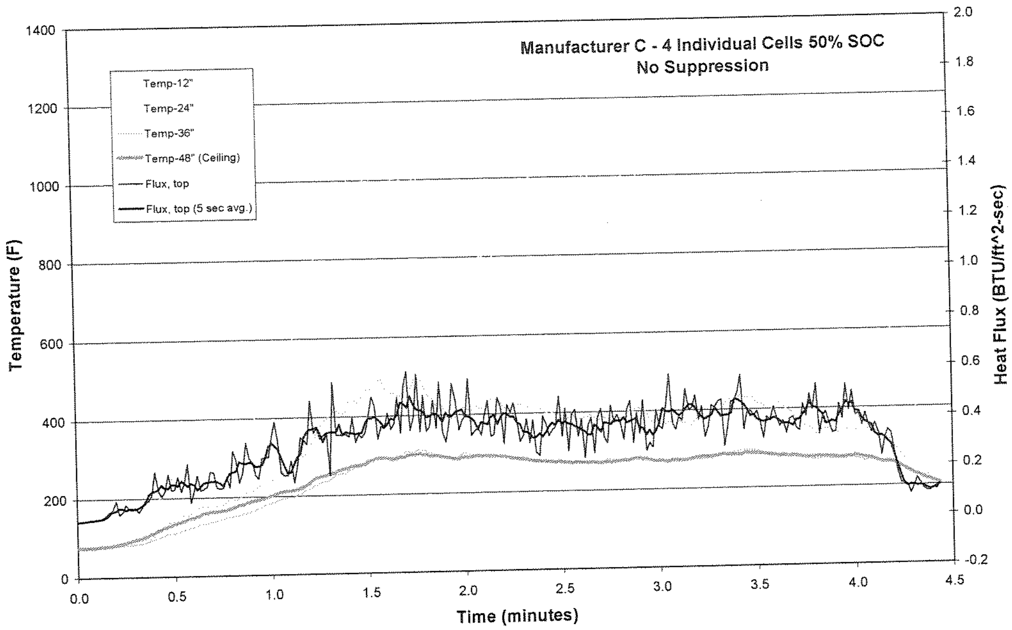


Figure 28. Tests with 16 Manufacturer B cells, without suppression (top), and with Halon 1301 application after cells began to vent (bottom).



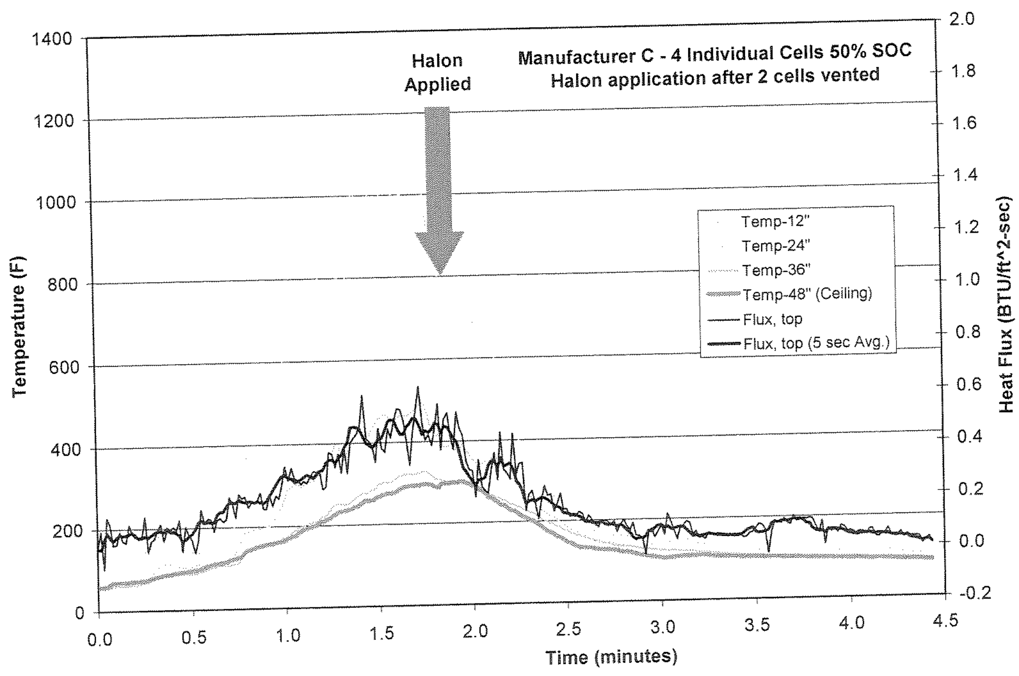
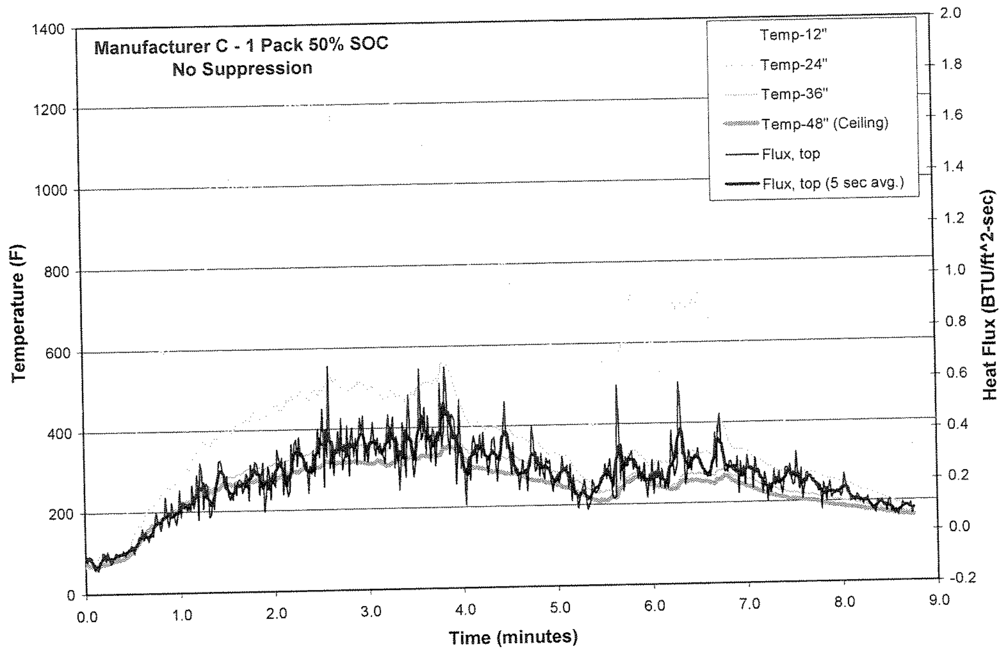


Figure 29. Tests with 4 Manufacturer C cells, without suppression (top), and with Halon 1301 application after cells began to vent (bottom).



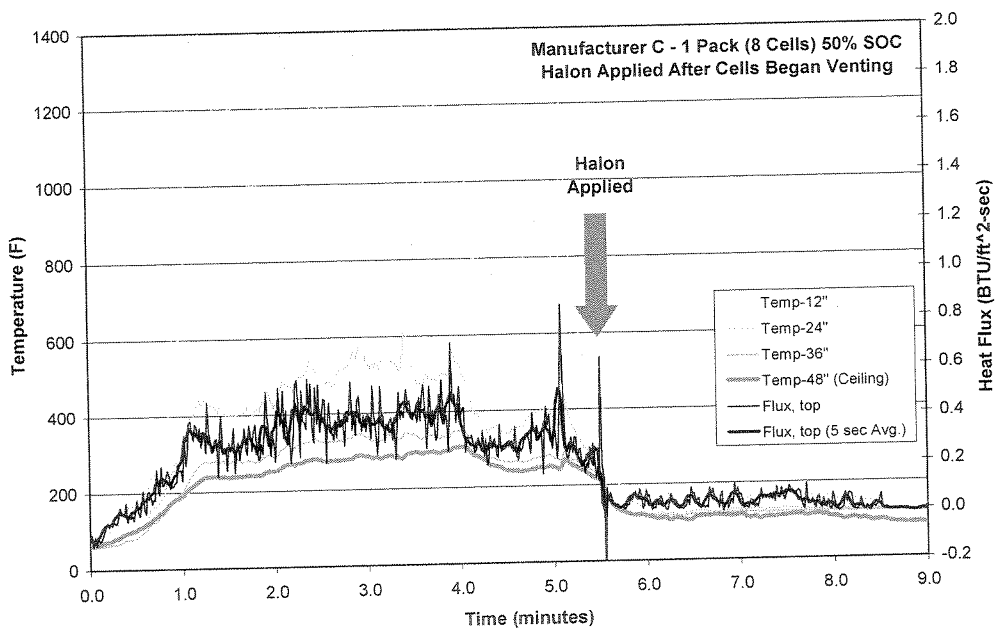


Figure 30. Tests with Manufacturer C battery packs, without suppression (top), and with Halon 1301 application after cells began to vent (bottom).

Conclusions

At the request of PRBA, Exponent conducted tests on lithium ion cells and battery packs at both 35% and 50% of full charge. The test setup and procedures are similar to those described in the FAA report entitled "Flammability Assessment of Bulk-Packed, Nonrechargeable Lithium Primary Batteries in Transport Category Aircraft". In particular, Exponent constructed a 64-cubic-foot test chamber, similar to that described in the FAA report. In that chamber, Exponent conducted flame attack tests on single, multiple, and bulk packaged lithium ion cells and battery packs. Exponent has also conducted tests to assess the impact on cargo hold liner material of lithium ion cells and battery packs attacked by fire; and tested the effectiveness of Halon 1301 in suppressing lithium ion cell and battery pack fires. Based on the testing conducted, Exponent has concluded the following:

1. Direct flame impingement on small, unpackaged quantities of bare cells and battery packs can lead to internal thermal runaway of individual cells and venting of gases. The vent gases are generally ignited by the pre-existing flame, increasing the total heat flux produced by the fire. In a few cases, cells will rupture and eject their contents.
2. Halon 1301 is very effective in controlling burning lithium ion cells.
3. The fires used in the testing program had minimal effects on bulk packaged lithium-ion cells at 50% or less state of charge. Direct flame impingement over a few minutes on bulk packages of cells did not lead to significant venting or involvement of the cells in the fire.
4. The aircraft cargo liner material used in the testing, which is commercially available and which we believe is typical, is capable of withstanding the tested flame impingement from burning gases vented by lithium-ion cells subjected to external heating.

References

1. Webster, Harry, “Flammability Assessment of Bulk-Packed, Nonrechargeable Lithium Primary Batteries in Transport Category Aircraft,” U.S. Department of Transportation, Federal Aviation Administration, DOT/FAA/AR-04/26, June 2004.

2. Federal Register, Vol. 69, No. 240, Wednesday, December 15, 2004, Part V, Department of Transportation, Research and Special Programs Administration, “49 CFR Parts 171, 172, 173 and 175 Hazardous Materials; Prohibition on the Transportation of Primary Lithium Batteries and Cells Aboard Passenger Aircraft; Final Rule.”

3. Mikolajczak, C.J., and D. Moore, “A Study of Passenger Aircraft Cargo Hold Environments”, Exponent Failure Analysis Associates Report, May 7, 2001.

4. http://www.mcgillcorp.com/products/cargoliners.asp, 2/28/05.

Appendix A

Cargo Hold Liner Data Sheets

M.C. GILL CORPORATION

Product Data Sheet

HIGH-PERFORMANCE COMPOSITE PRODUCTS SINCE 1945

Gilliner™ 1066 Laminate

August 1996

Description

Gilliner 1066 is a general purpose, fiberglass cloth reinforced polyester laminate.

Applications

Aircraft cargo compartment liner.
LD-3 container walls.

Features

- Good impact, puncture and corrosion resistance.
- Service temperature: To 180°F.

Availability

Thickness:	.010", .016", .023", .030", .045", .060", .075" and .090".
Length:	Sheets up to 14'. Available in rolls up to 60" wide by 150' or longer in thickness up to .060".
Width:	36", 48", 60", or 72". (Roll stock: 60" max. width.)
Color:	White, unless otherwise specified.

Construction

Resin: Fire resistant polyester.
Reinforcement: Proprietary fiberglass cloth

Standard Tolerances

Thickness:	+/- 10%
Length:	+ 0.5", -0"
Width:	+ 0.5", -0"
Color:	Commercial

Alternative Gill Products

Product Number	Difference
Gilliner 1066R	Roll stock in lengths up to 150 linear feet long and in thickness of .045" and less
Gilliner 1066T	Gilliner 1066 with a 1 mil white Tedlarp film bonded on one surface for decorative or exterior service.
Gilliner 1076	Lower priced, similar to 1066.
Gilliner 1366T	High puncture resistant version of Gilliner 1066.

Properties of Gilliner 1066

Based on .060" thick laminate (Unless noted)

Property	Test Method	Unit	Type 13	Type 16	Type 23
Weight	ASTM 29	lb/sq ft (kg/sq m)	0.122 (0.60)	0.186 (0.91)	0.215 (1.05)
Thickness	ASTM C366	inch (mm)	0.012 (0.30)	0.018 (0.46)	0.020 (0.51)
Water Absorption	FTMS 406-7031	%	1.49	1.31	1.25
Impact Note 1	DMS 1946	ft-lb (N-m)	6 (8.1)	9 (12.2)	11 (14.9)
Edge Bearing Strength Warp Fill	BMS 8-262	ksi (MPa) ksi (MPa)	28.4 (195.9) 32.2 (222.1)	39.4 (271.7) 33.7 (232.4)	28.1 (193.8) 24.5 (169.0)
Bolted Joint Strength Warp Fill	DMS 1946	lb (N) lb (N)	258 (1,148) 240 (1,068)	169 (752) 179 (796)	401 (1,784) 365 (1,624)
Flammability - 60 Second Vertical Self-Extinguishing Time Burn Length Drip Extinguishing Time	FAR 25.853	second inch (mm) second	0 1.1 (27.9) 0	0 0.9 (22.8) 0	0 0.5 (12.7) 0
Flammability - 45 Degree Self-Extinguishing Time Glow Time Penetration	FAR 25.853	second second ---	0 0 None	0 0 None	0 0 None
Oil Burner Note 2	FAR 25.855	---	Pass	Pass	Pass

Note 1 - Determined using Gardner Model 11K3 impactor and 2 lb dart.
Note 2 - Test performed by U. S. Testing in accordance with the procedure outlined in Appendix F, Part III of FAR 25.855, "Oil Burner - Burn through Resistance".

Property	Test Method	Unit	Type 30	Type 45	Type 60
Weight	ASTM C29	lb/sq ft (kg/sq m)	0.290 (1.42)	0.439 (2.14)	0.564 (2.75)
Thickness	ASTM C366	inch (mm)	0.031 (0.79)	0.045 (1.14)	0.062 (1.57)
Water Absorption	FTMS 406-7031	%	1.58	2.85	2.11
Impact Note 1	DMS 1946	ft-lb (N-m)	17 (23.1)	25 (33.9)	35 (47.5)
Edge Bearing Strength Warp Fill	BMS 8-262	ksi (MPa) ksi (MPA)	30.3 (209.0) 31.6 (217.9)	32.1 (221.4) 61.1 (421.4)	37.7 (260) 42.9 (296.9)
Bolted Joint Warp Fill	DMS 1946	lb (N) lb (N)	239 (1,063) 274 (1,219)	453 (2,015) 569 (2,531)	653 (2,905) 409 (1,819)
Flammability - 60 Second Vertical Self-Extinguishing Time Burn Length Drip Extinguishing Time	FAR 25.853	second inch (mm) second	0 0.1 (2.54) 0	0 0.2 (5.08) 0	0 0.1 (2.54) 0
Flammability - 45 Degree Self Extinguishing Time Glow Time Penetration	FAR 25.853		0 0 None	0 0 None	0 0 None
Oil Burner Note 2		---	Pass	Pass	Pass

Note 1 - Determined using Gardner Model 11K3 impactor and 2 lb dart.
Note 2 - Test performed by U. S. Testing in accordance with the procedure outlined in Appendix F, Part III of FAR 25.855, "Oil Burner - Burn through Resistance"

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August 2004

Gillfab™ 1367A Laminate

Description

Gillfab™ 1367A is a high impact resistant, low smoke and toxicity, fiberglass reinforced phenolic laminate.

Applications

Aircraft cargo compartment liner.

Features

- High mechanical strength, puncture resistance and corrosion resistance.
- Service temperature range: To 220°F.
- White Tedlar® overlay on face side for surface reflectivity and resistance to cleaning solutions.

Specifications

- Boeing BMS 8-223, Class 2, Grade B, Types 13 through 40
- McDonnell Douglas DMS 2419 Classes 1 and 2, Types 13 through 40
- Airbus 2550 MIM 000800, Airbus Types 1 through 5
- FAR 25.853 and 25.855

Availability

Thickness:	0.013", 0.020", 0.025", 0.030", 0.040"., 0.045", 0.060"
Length:	Up to 168". Also available in rolls up to 150' (if .040" or thinner and 60" or narrower).
Width:	Up to 72".
Color:	White Tedlar® on face side, amber on back side; or amber both sides (DMS 2419, Class 2)

Construction

Resin: Modified phenolic.
Reinforcement: Woven glass cloth.
Surface: 1 mil Tedlar overlay.

Standard Tolerances

Thickness:	+/-0.003" (0.013" and 0.020"); all other ± 10%
Length:	+ 0.5", - 0"
Width:	+ 0.5", - 0"
Warp Twist:	3% of dimension measured

Alternative M.C. Gill Products

Product Number	Difference
Gillfab 1167 Laminate	Qualified to DMS 2226 Ty 1 Class 1. Similar, but different thickness requirements.
Gillfab 1366 Laminate	High impact resistant cargo liner. Polyester resin system has higher smoke emission; qualified to Boeing Specification BMS 8-2 Cl 2 Gr A.
Gillfab 1367 Laminate	Predecessor to 1367A; similar, qualified to BMS8-223, Types 13 through 70
Gillfab 1367C Laminate	Same as 1367A but manufactured in roll stock in lengths up to 150' and up to .040" thick
Gillfab 1367M	Qualified to BMS8-223, Class 4, Types 13 through 50. Thinner and lower in weight for corresponding types.
Gillfab 1367E	Qualified to BMS8-223, Class 2, Grade A, Types 13 through 70. Tedlar® surface on both sides of laminate. Also available in Types 45, 60, and 90 (these are not specified types in BMS8-223).

Properties of Gillfab™ 1367A Laminate, According to BMS8-223, and DMS 2419 Types 13 and 20 Typical Properties

PROPERTY	UNITS	TEST METHOD	TYPE 13	TYPE 20
Weight	lb/ft² (kg/m²)	BMS8-223	0.121 (0.59)	0.195 (0.95)
Thickness	inches (mm)	BMS8-223	0.013 (0.33)	0.021 (0.53)
Water Absorption	%	ASTM D 570	0.8	1.1
Impact Strength	ft-lb (N-m)	BSS7326	11 (14.9)	15 (20.4)
Impact Strength	ft-lb (N-m)	DMS2419	>32 (>43.4)	>40 (>54.3)
Climbing Drum Peel[1], Warp Fill	in-lb (N-m)/3 in width	BMS8-223	56 (6.3) ---	55 (6.2) 66 (7.5)
Edge Bearing Strength, Warp Fill	ksi (MPa)	BMS8-223	37 (254) 34 (235)	39 (268) 36 (249)
Tedlar Peel, Warp Fill	lbs./in.	BMS8-223	3.0 (54) 2.6 (46)	3.7 (66) 2.7 (48)
Flexural Strength[2] Flexural Modulus	ksi (MPa) msi (GPa)	AMS-STD-401	NR NR	27 (184) 2.1 (14.2)
Tensile Strength[2] Tensile Modulus	ksi (MPa) msi (GPa)	DMS 2226	54.5 (375.8) 3.16 (21.8)	60.6 (417.8) 2.5 (17.2)
Bolted Joint Strength	lbs. (N)	DMS 2419	103.3 (46.9)	193 (87)
Flammability -60 Second Vertical Self-Extinguishing Time Burn Length Drip Extinguishing Time	seconds inches (mm) seconds	FAR Part 25, Appendix F, Part I	0 2.3 (57) None	0 2.7 (68) None
Flammability - 45 Degree Self-Extinguishing Time Glow Time Penetration	seconds seconds ---	FAR Part 25, Appendix F, Part I	0 1.7 None	0.5 1.8 None
Smoke Density	D_s	ASTM F 814-83	21.7	35.3
Burn Through Resistance	FAR Part 25, Appendix F, Part III		Pass	Pass

1. On Type 13, drum peel in the fill direction resulted in fabric tearing and no data could be obtained.
2. Reported only in the warp direction.
NR = No Requirement

Properties of Gillfab™ 1367A Laminates, According to BMS8-223, and DMS 2419
Types 30 and 40
Typical Properties

PROPERTY		UNITS	TEST METHOD	TYPE 30	TYPE 40
Weight		lb/ft² (kg/m²)	BMS8-223	0.293 (1.43)	0.375 (1.83)
Thickness		inches (mm)	BMS8-223	0.031 (0.79)	0.040 (1.02)
Water Absorption		%	ASTM D 570	0.9	1.1
Impact Strength		ft-lb (N-m)	BSS7326	19 (25.8)	25 (33.9)
Impact Strength		ft-lb (N-m)	DMS2419	>50 (>67.8)	>50 (>67.8)
Climbing Drum Peel,	Warp Fill	in-lb (N-m)/3 in width	BMS8-223	16 (21.7) 24 (32.6)	15.7 (21.3) 15.7 (21.3)
Edge Bearing	Warp Fill	ksi (MPa) ksi (MPa)	BMS8-223	40 (275) 38 (262)	42 (290) 40 (275)
Flexural Strength[1] Flexural Modulus[1]		ksi (MPa) msi (GPa)	AMS-STD-401	39.1 (267) 2.57 (17.7)	NR NR
Tedlar Peel	Warp Fill	lb/in (kg/m)	BMS8-223	3.2 (57.1) 2.8 (50)	3.9 (69.6) 4.2 (75.0)
Tensile Strength[1] Tensile Modulus[1]		ksi (Mpa) msi (GPa)	BMS8-223	57.9 (399.2) 2.50 (17.2)	NR NR
Bolted Joint Strength		lb (N)	DMS 2419	286.9 (130.3)	NR
Flammability -60 Second Vertical Self-Extinguishing Time Burn Length Drip Extinguishing Time		seconds inches (mm) seconds	FAR Part 25, Appendix F, Part I	0 2.6 (65) None	0 1.7 (44) None
Flammability - 45 Degree Self-Extinguishing Time Glow Time Penetration		seconds seconds ---	FAR Part 25, Appendix F, Part I	0 1.7 None	0 0 None
Smoke Density		D_s	ASTM F814-83	31.6	42.8
Burn Through Resistance		---FAR Part 25, Appendix F, Part III		Pass	Pass

1. Reported only in the warp direction.
NR = No Requirement

Properties of Gillfab™ 1367A Laminate According to Airbus Specification 2550 M1M 00800
Types 1, 2, 3, 4 and 5
Typical Properties

PROPERTY	UNITS	TEST METHOD	Airbus Ty 1	Airbus Ty 2	Airbus Ty 3	Airbus Ty 4	Airbus Ty 5
Weight	kg/m² (psf)	----	0.61 (0.125)	1.17 (0.240)	1.87 (0.383)	2.1 (0.430)	2.7 (0.546)
Thickness	mm (in)		0.33 (0.013)	0.61 (0.024)	0.99 (0.039)	1.14 (0.045)	1.47 (0.058)
Tensile Strength Warp Fill	KN/cm² (ksi)	ASTM D638	37.3 (54.1) 36.7 (53.3)	47.9 (69.5) 42.0 (60.9)	32.8 (47.6) 31.9 (46.2)	38.9 (56.4) 31.1 (45.1)	36.1 (52.4) 32.9 (47.7)
Impact Strength	N-m (ft-lbs)	ASTM D5420	17 (12)	24 (18)	34 (25)	34 (25)	44 (32)
Water Absorption	%	ISO 62, Method 1	0.7	0.5	0.7	0.6	0.5
Flexural Strength Warp Fill	KN/cm² (ksi)	ASTM D790	NR	29.3 (42.5) 25.2 (36.6)	29.0 (42.1) 26.3 (38.1)	27.7 (40.1) 22.4 (32.5)	26.9 (39.0) 23.6 (34.3)
Flexural Modulus Warp Fill	KN/cm² (msi)	ASTM D790	NR	929 (1.35) 921 (1.34)	1933 (2.80) 1627 (2.36)	1598 (2.32) 1558 (2.26)	1611 (2.34) 1551 (2.26)
Flammability – 60 Second Vertical Extinguishing Time Burn Length Drip Ext. Time	seconds mm (inches) seconds	FAR Part 25, Appendix F, Part I	0 4.8 (0.2) 0	0 4.8 (0.2) 0	0 4.6 (0.2) 0	0 4.8 (0.2) 0	0 4.3 (0.17) 0
Flammability – 45 Degree Extinguishing Time Flame Penetration After Glow	seconds seconds	FAR Part 25, Appendix F, Part I	0 None 0	0 None 0	0 None 0	0 None 0	0 None 0
Burn Through Resistance	FAR Part 25, Appendix F, Part III		Pass	Pass	Pass	Pass	Pass

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Appendix B

Data from Testing

Calibration Tests

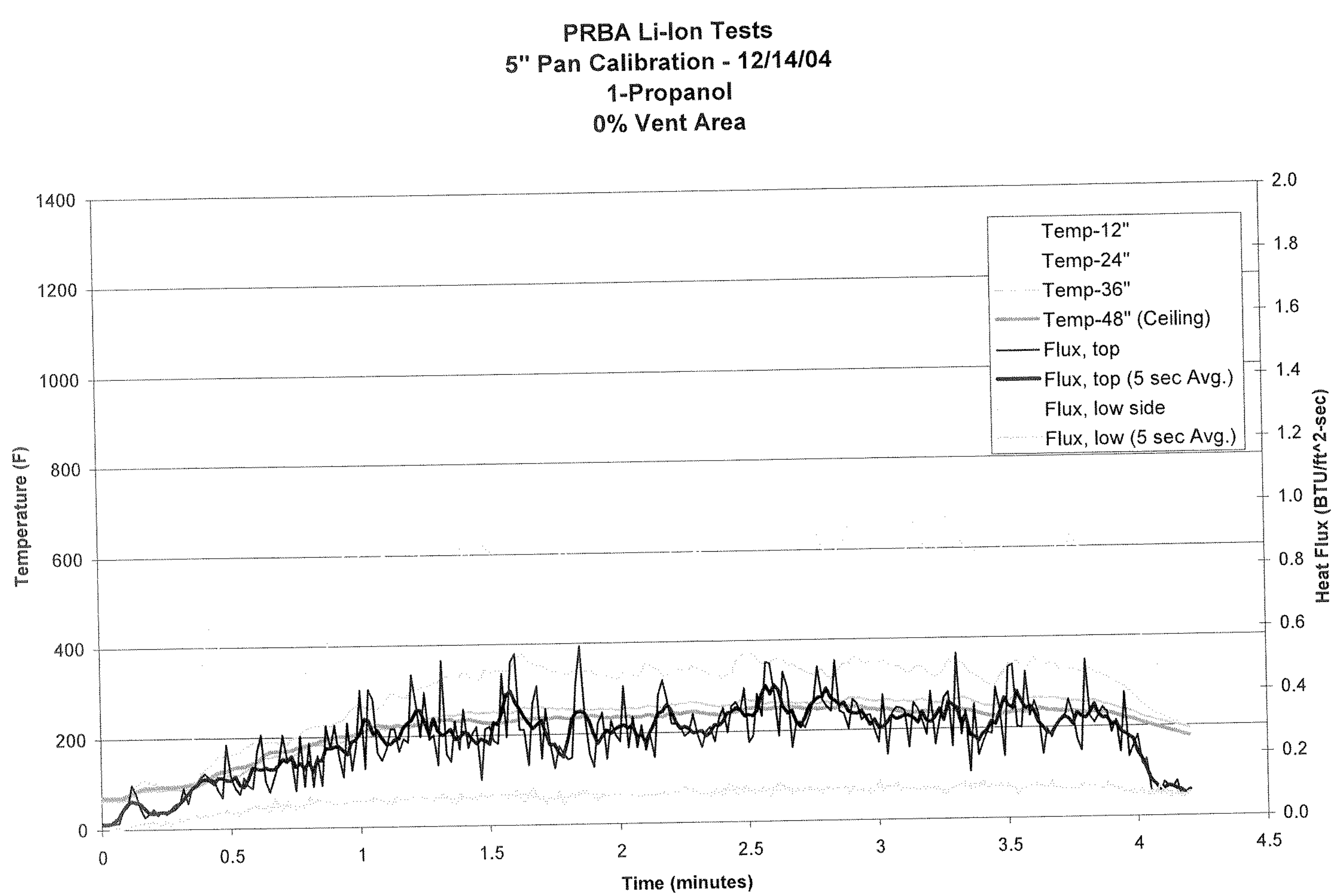

Figure B-1. Calibration Test 12/14/04, 5” Pan, 0% vent area.

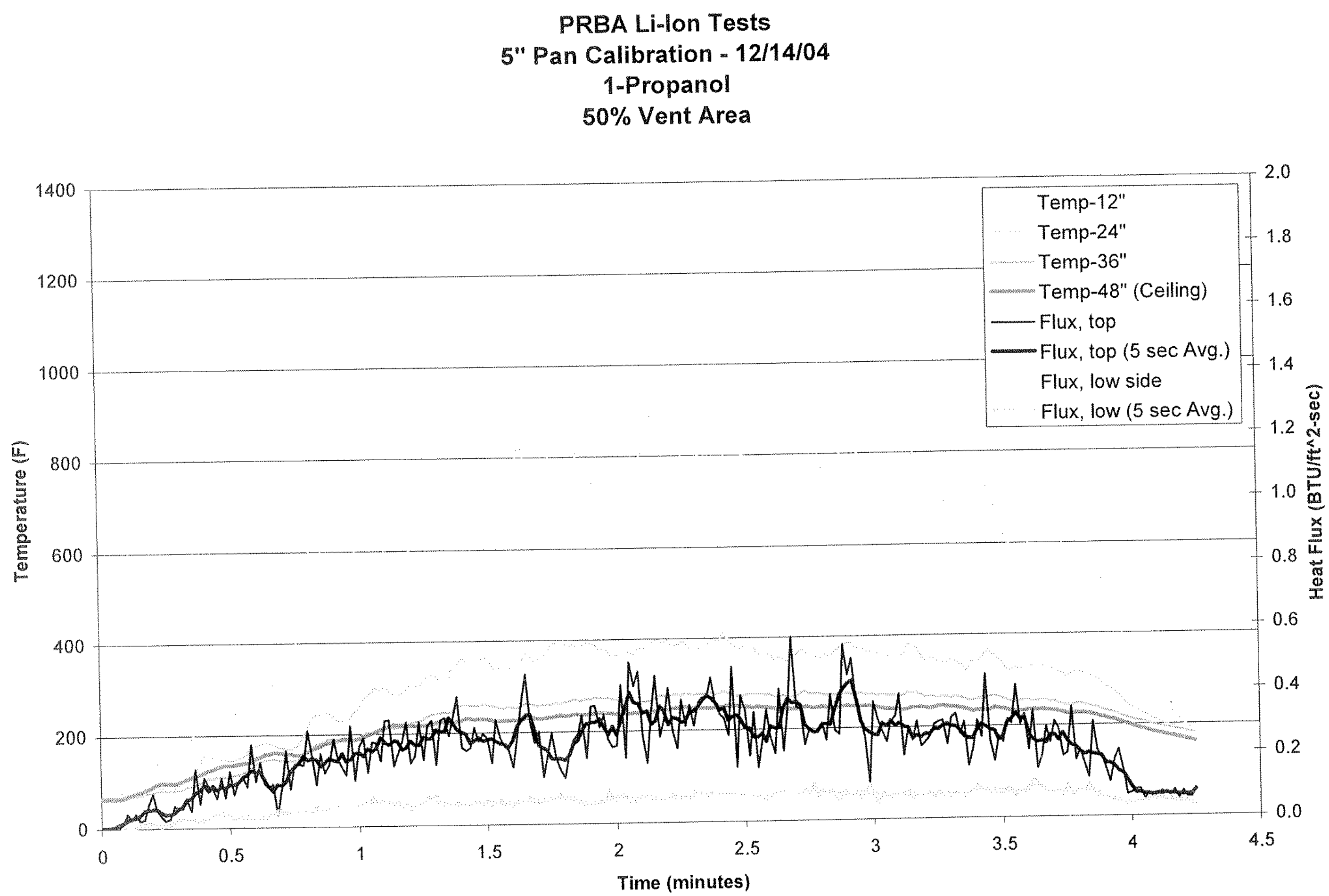

Figure B-2. Calibration Test 12/14/04, 5" Pan, 50% vent area.

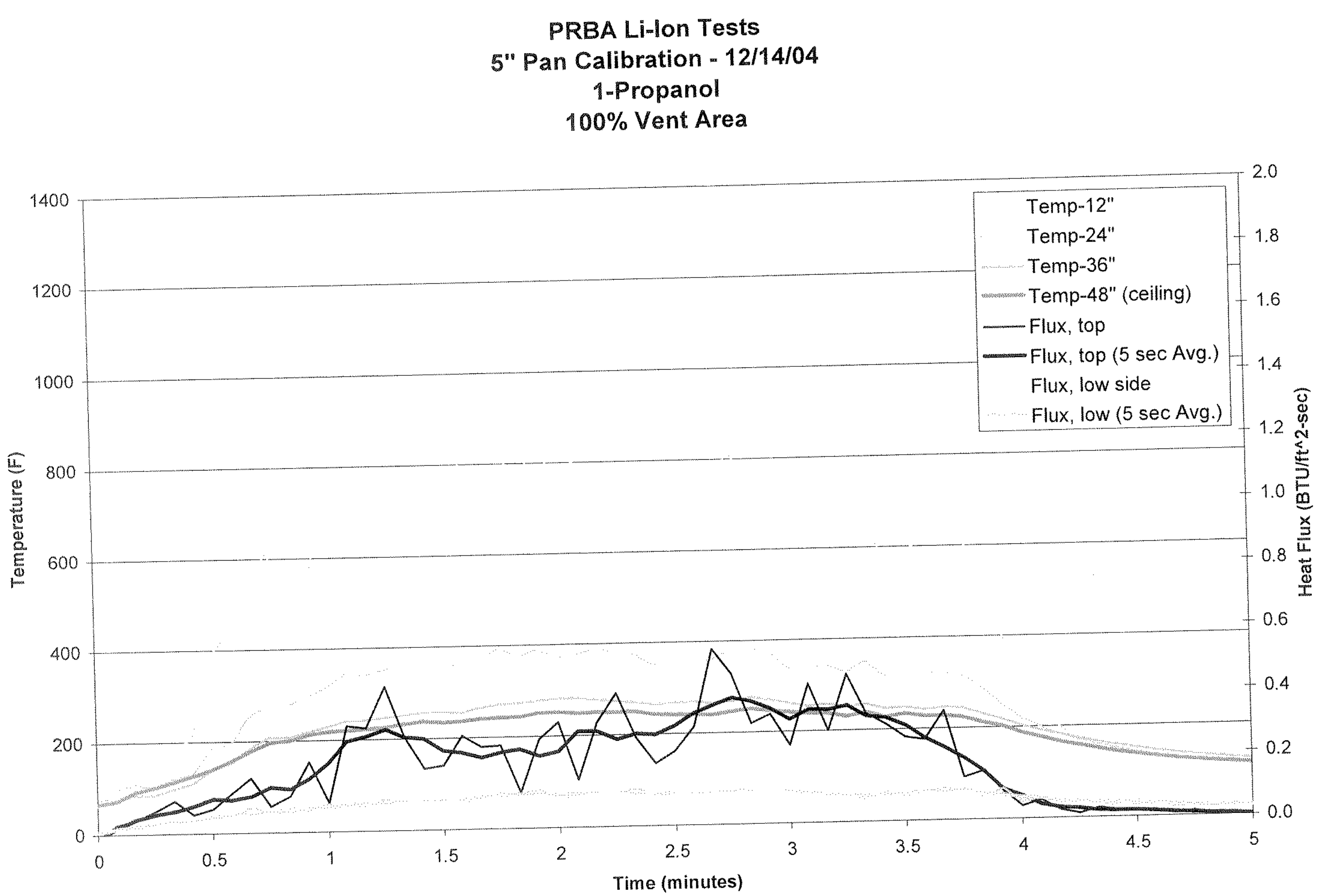

Figure B-3. Calibration Test 12/14/04, 5" Pan, 100% vent area.

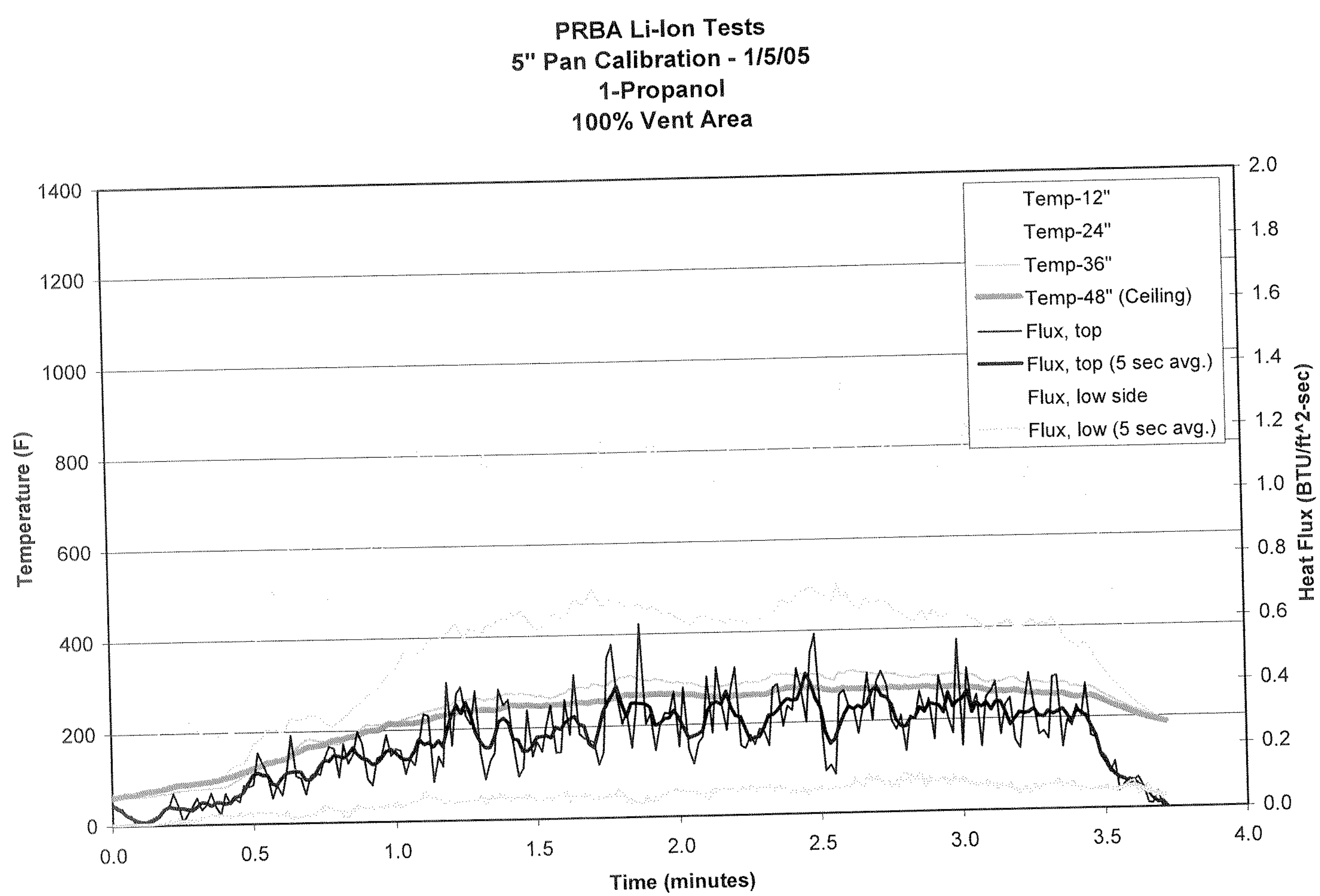

Figure B-4. Calibration Test 1/5/05, 5" Pan, 100% vent area.

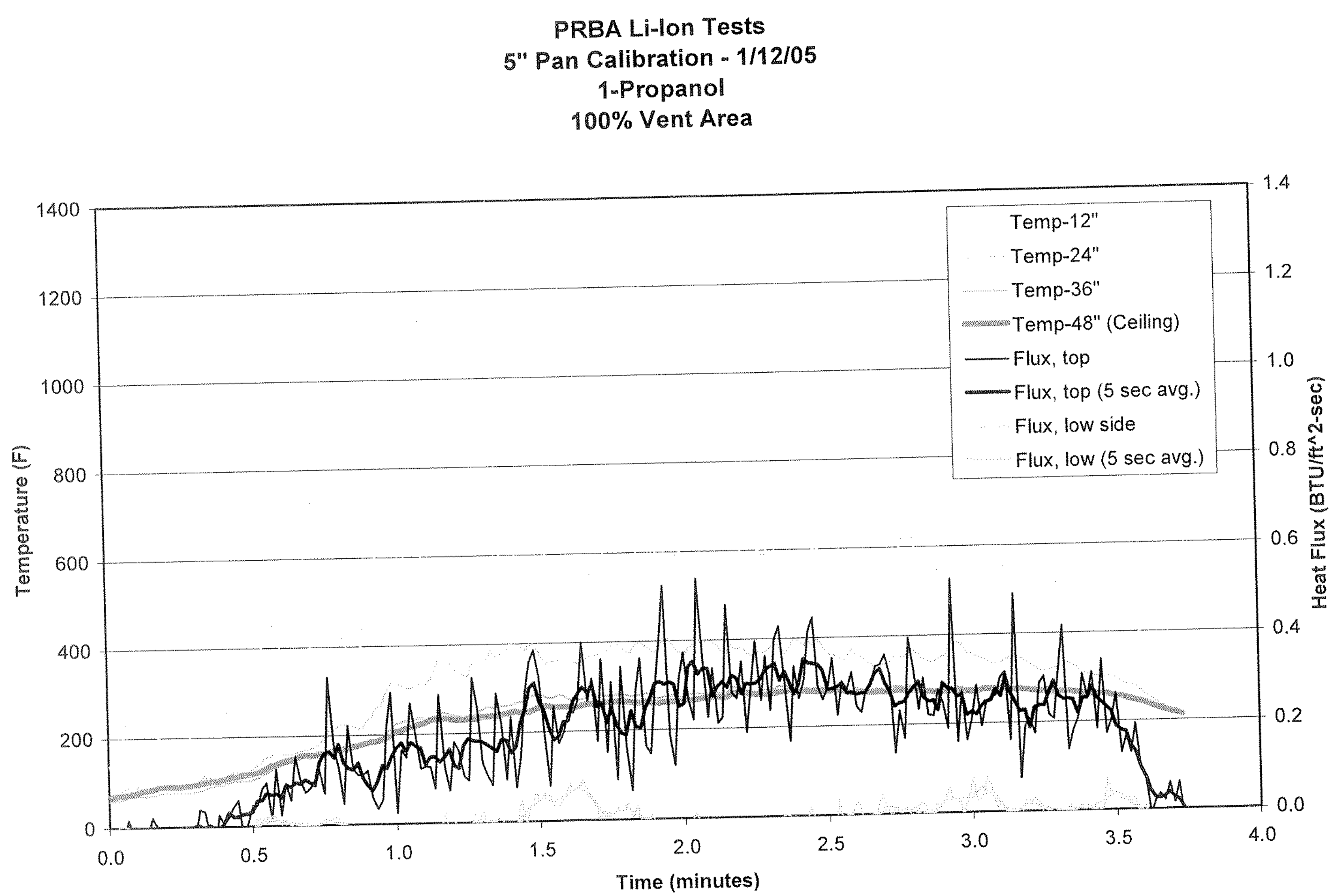

Figure B-5. Calibration Test 1/12/05, 5" Pan, 100% vent area.

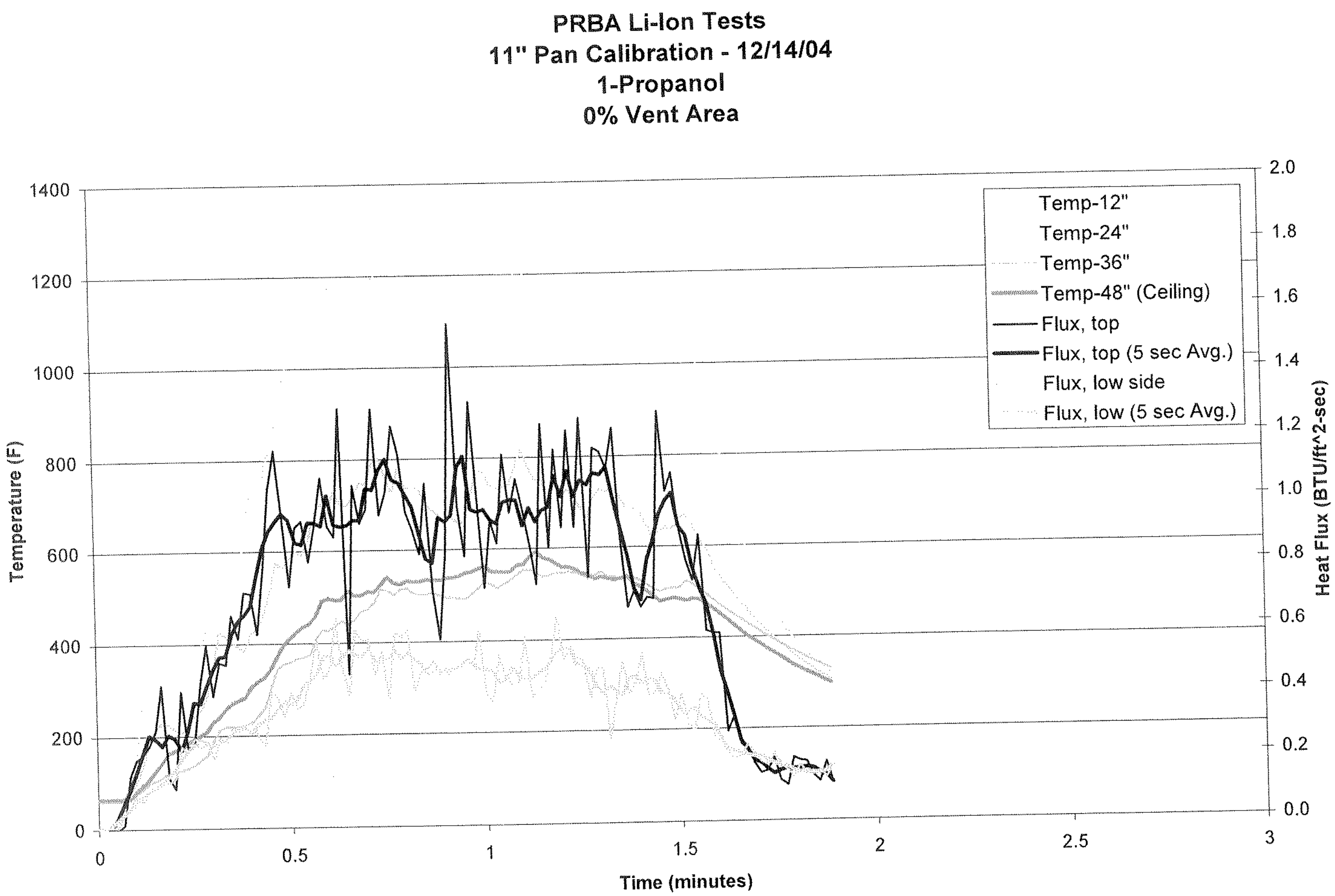

Figure B-6. Calibration Test 12/14/04, 11" Pan, 0% vent area.

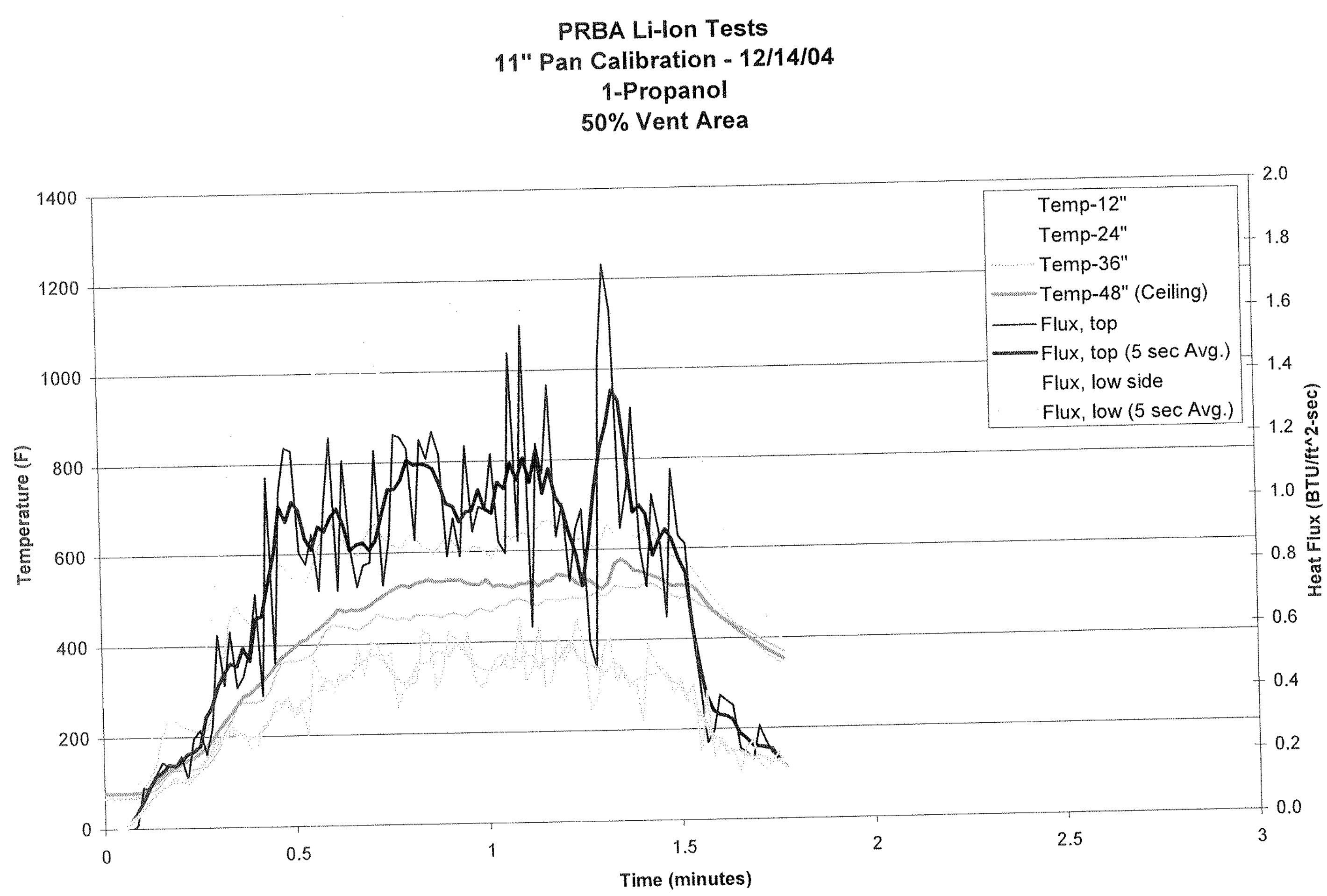

Figure B-7. Calibration Test 12/14/04, 11" Pan, 50% vent area.

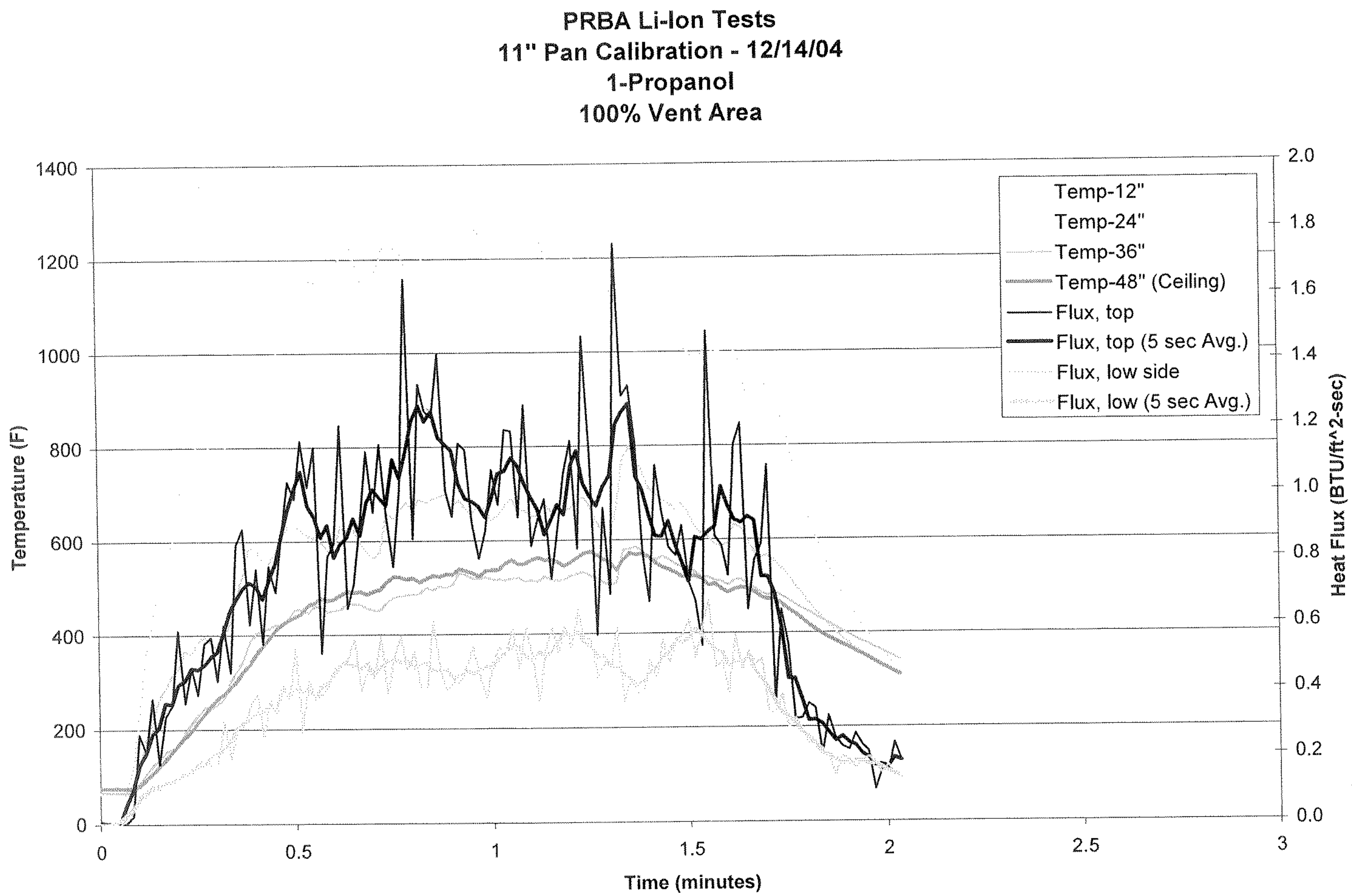

Figure B-8. Calibration Test 12/14/04, 11" Pan, 100% vent area.

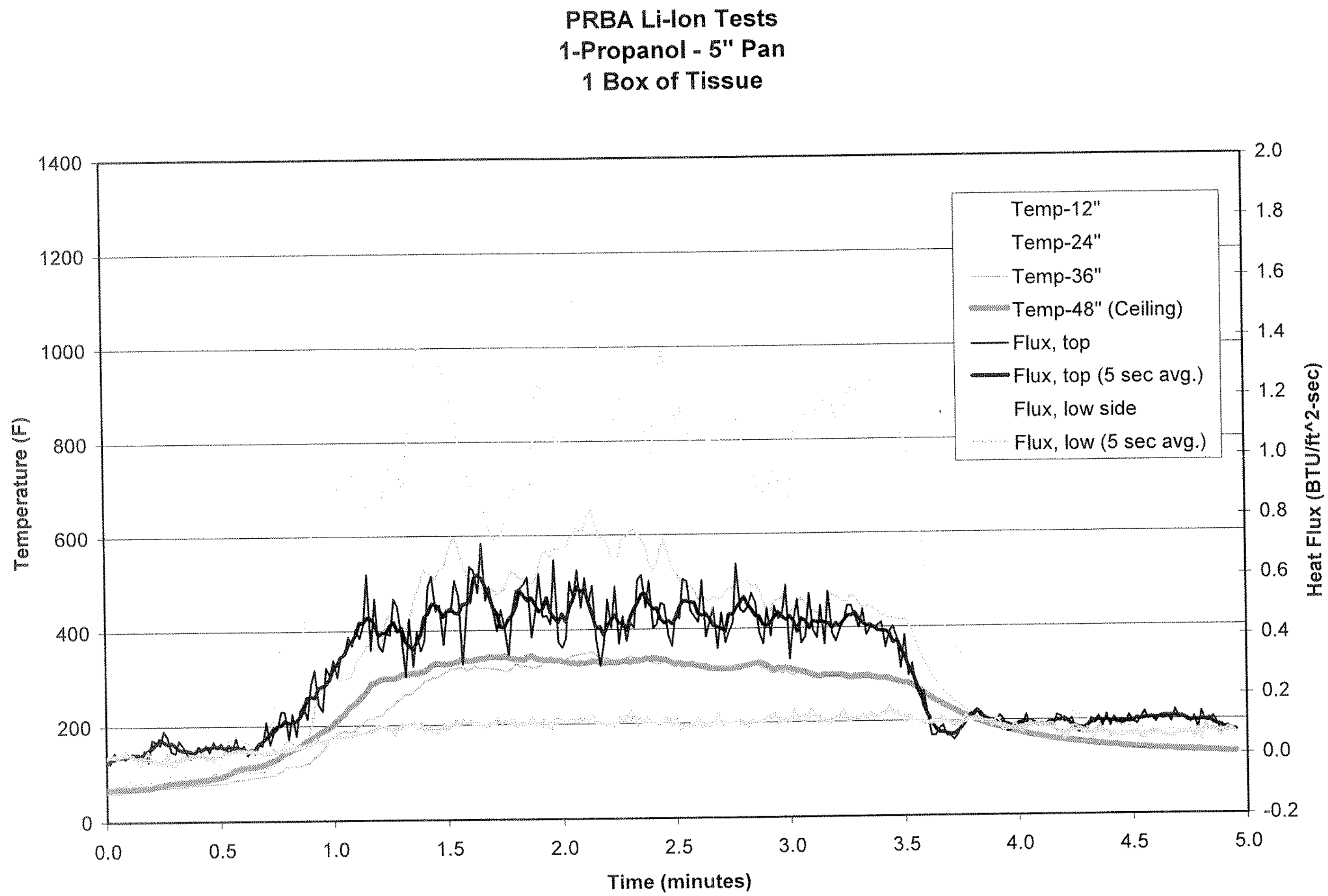

Figure B-9. Comparison Test—Box of facial tissues.

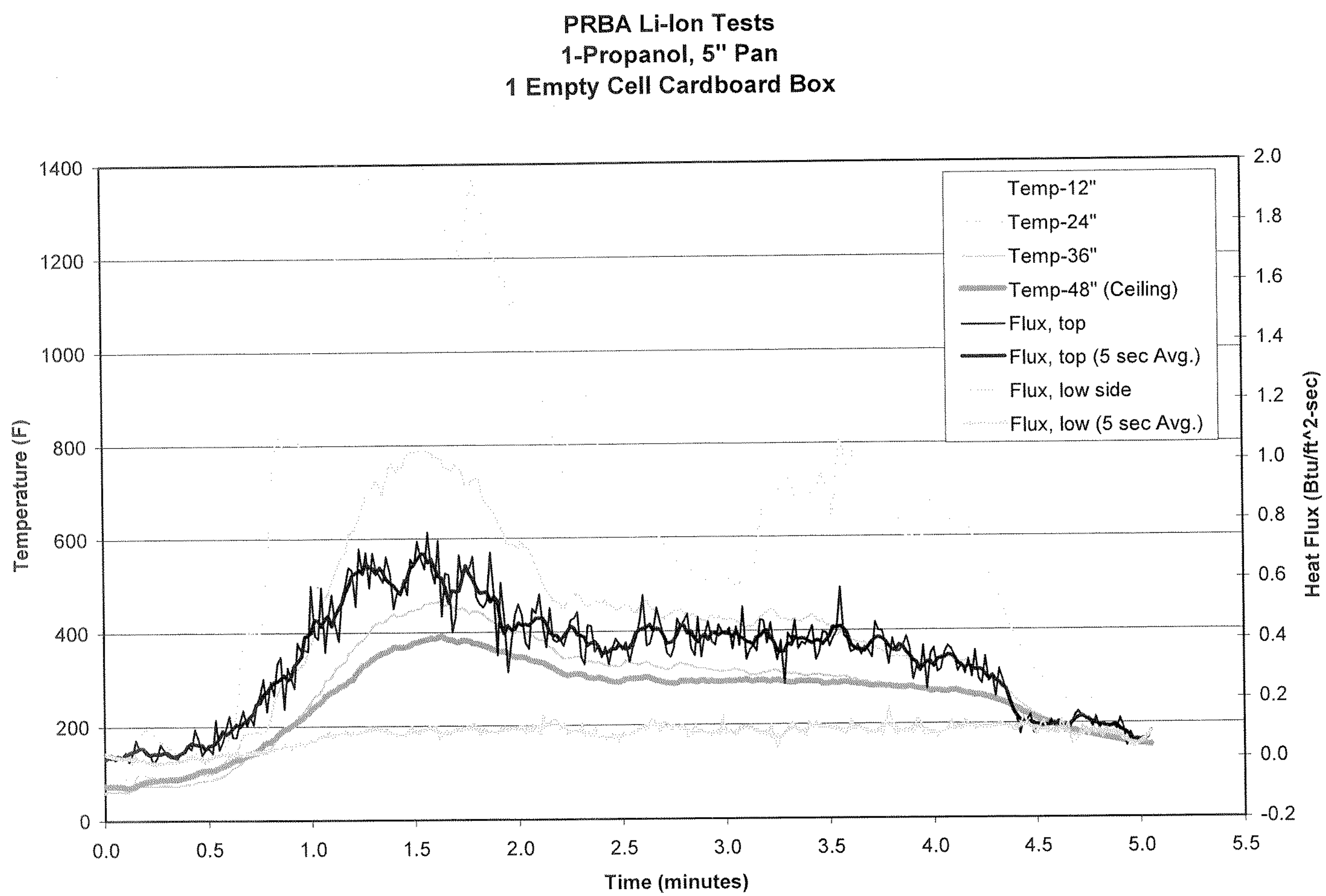

Figure B-10. Comparison Test—Manufacturer A packaging material (empty cardboard box).

Manufacturer A Tests

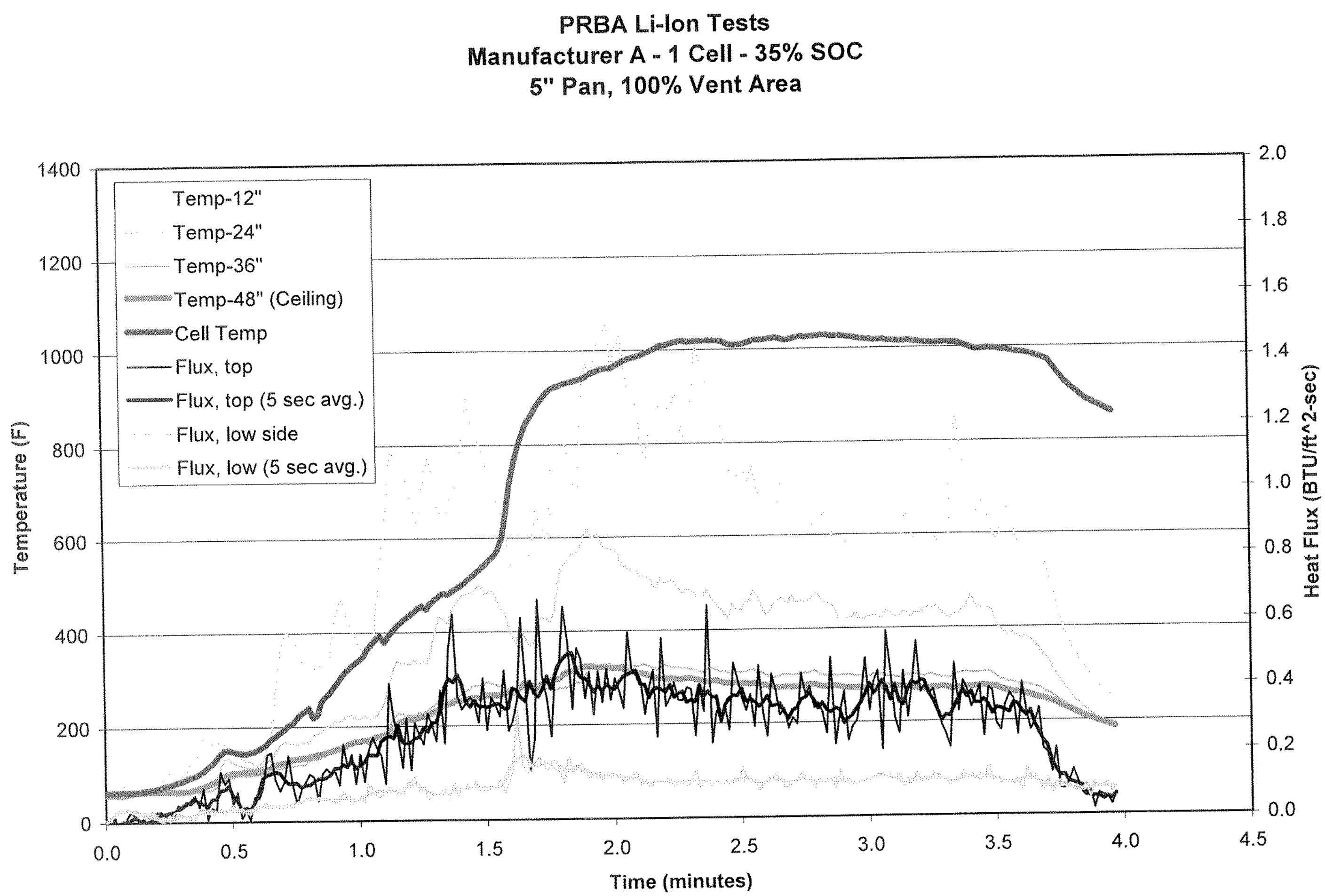

Figure B-11. Manufacturer A, single cell, 35% SOC.

Manufacturer A Tests

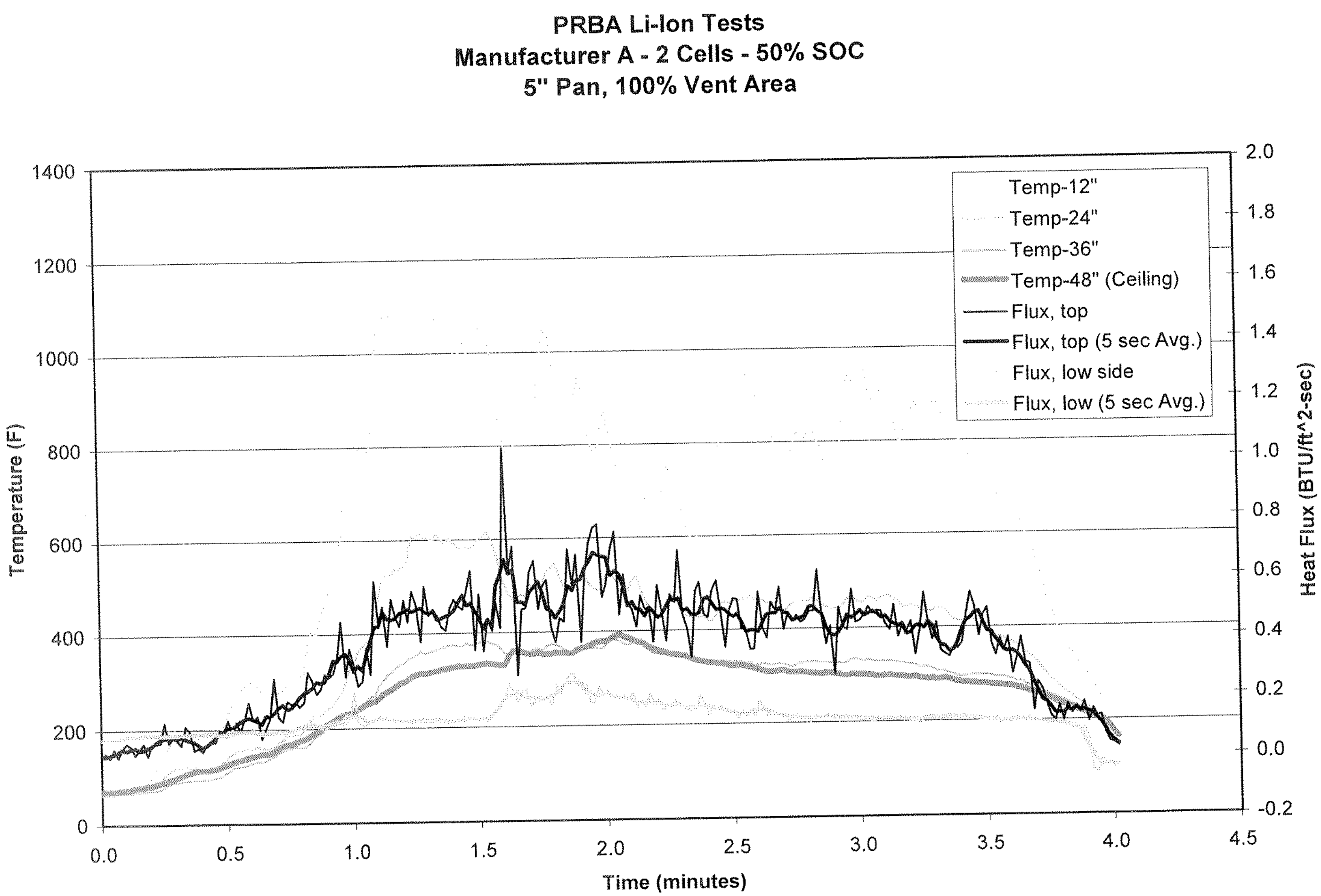

Figure B-12. Manufacturer A, 2 cells, 50% SOC.

Manufacturer A Tests

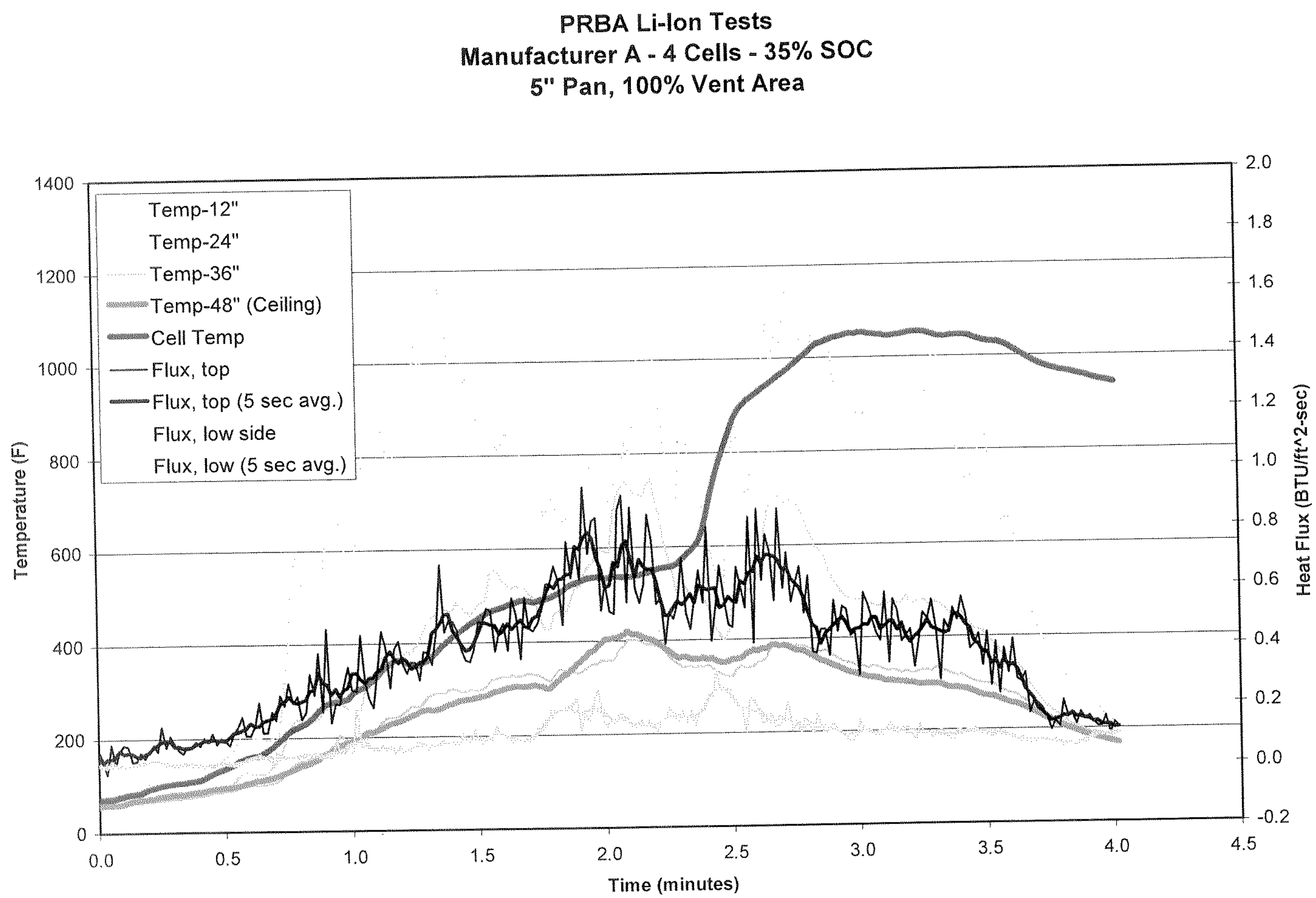

Figure B-13. Manufacturer A, 4 cells, 35% SOC.

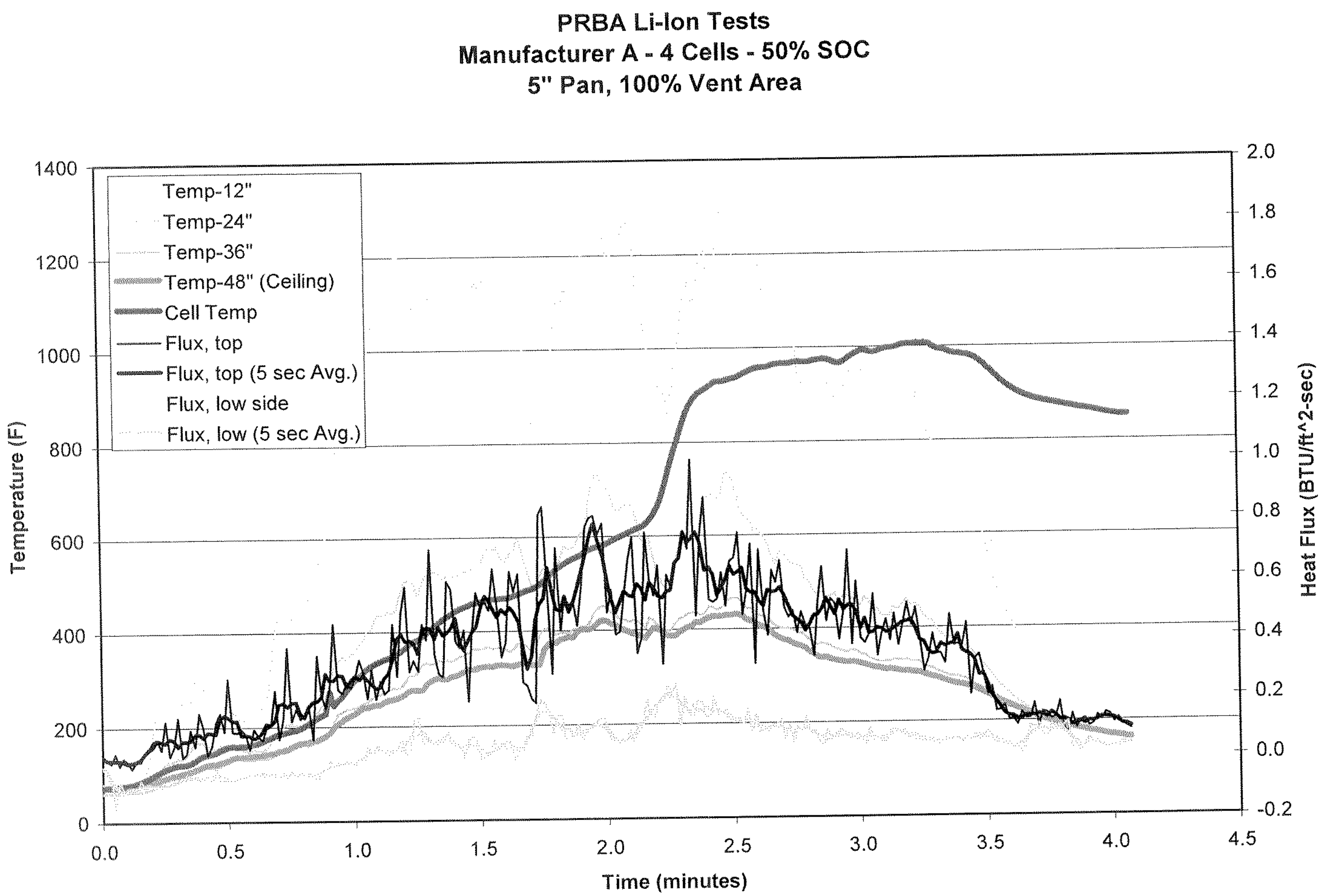

Figure B-14. Manufacturer A, 4 cells, 50% SOC.

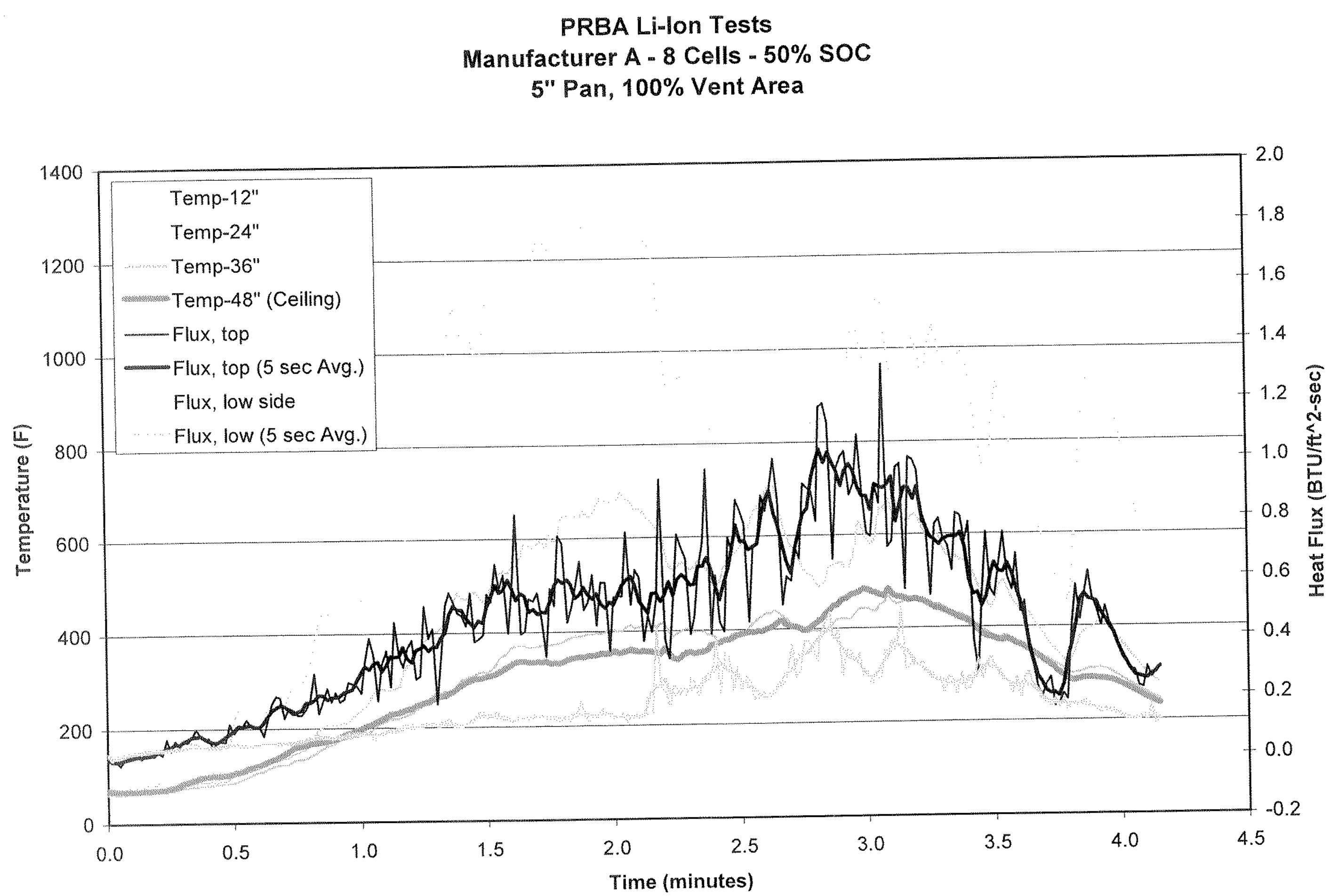

Figure B-15. Manufacturer A, 8 cells, 50% SOC.

Manufacturer A Tests

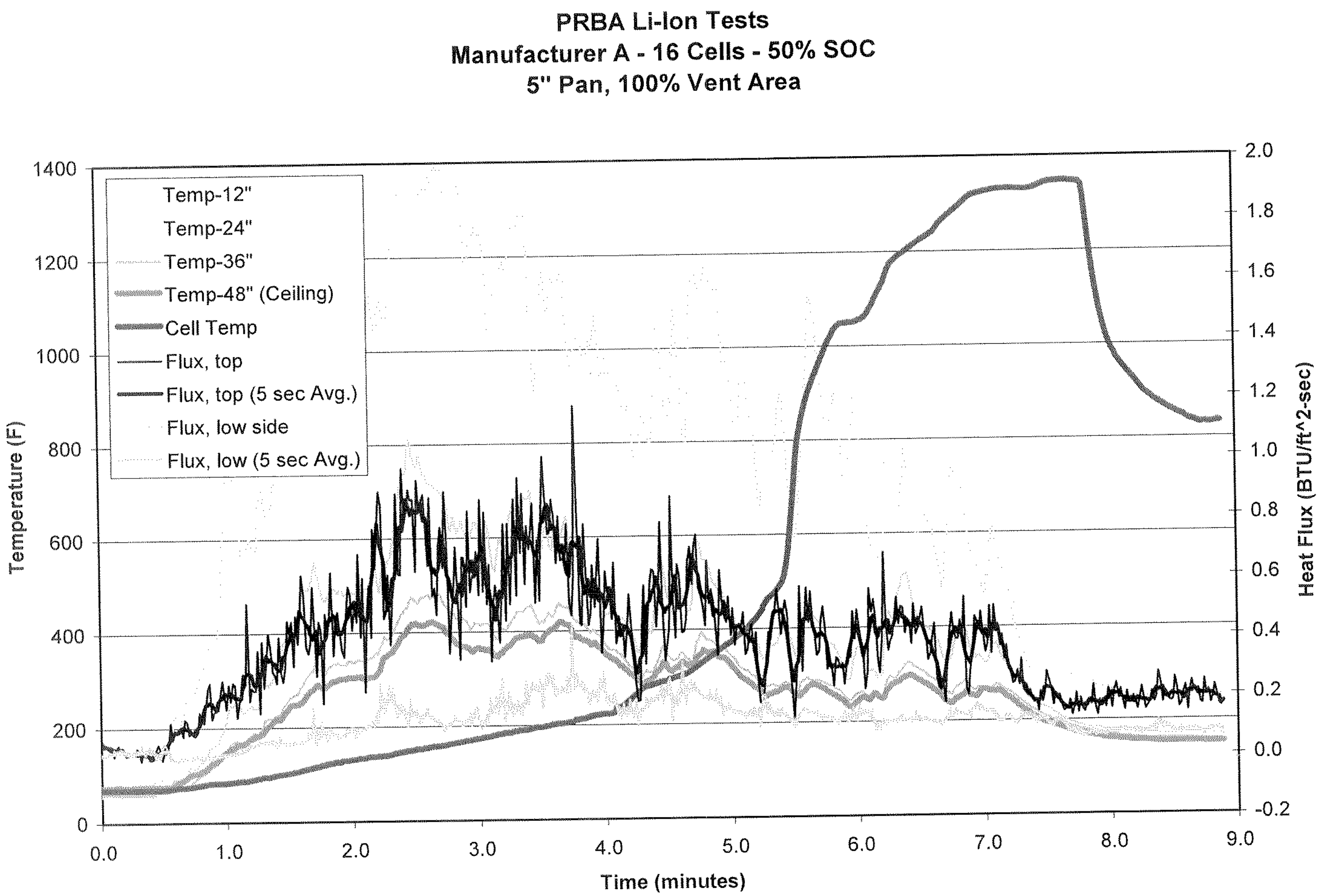

Figure B-16. Manufacturer A, 16 cells, 50% SOC.

Manufacturer A Tests

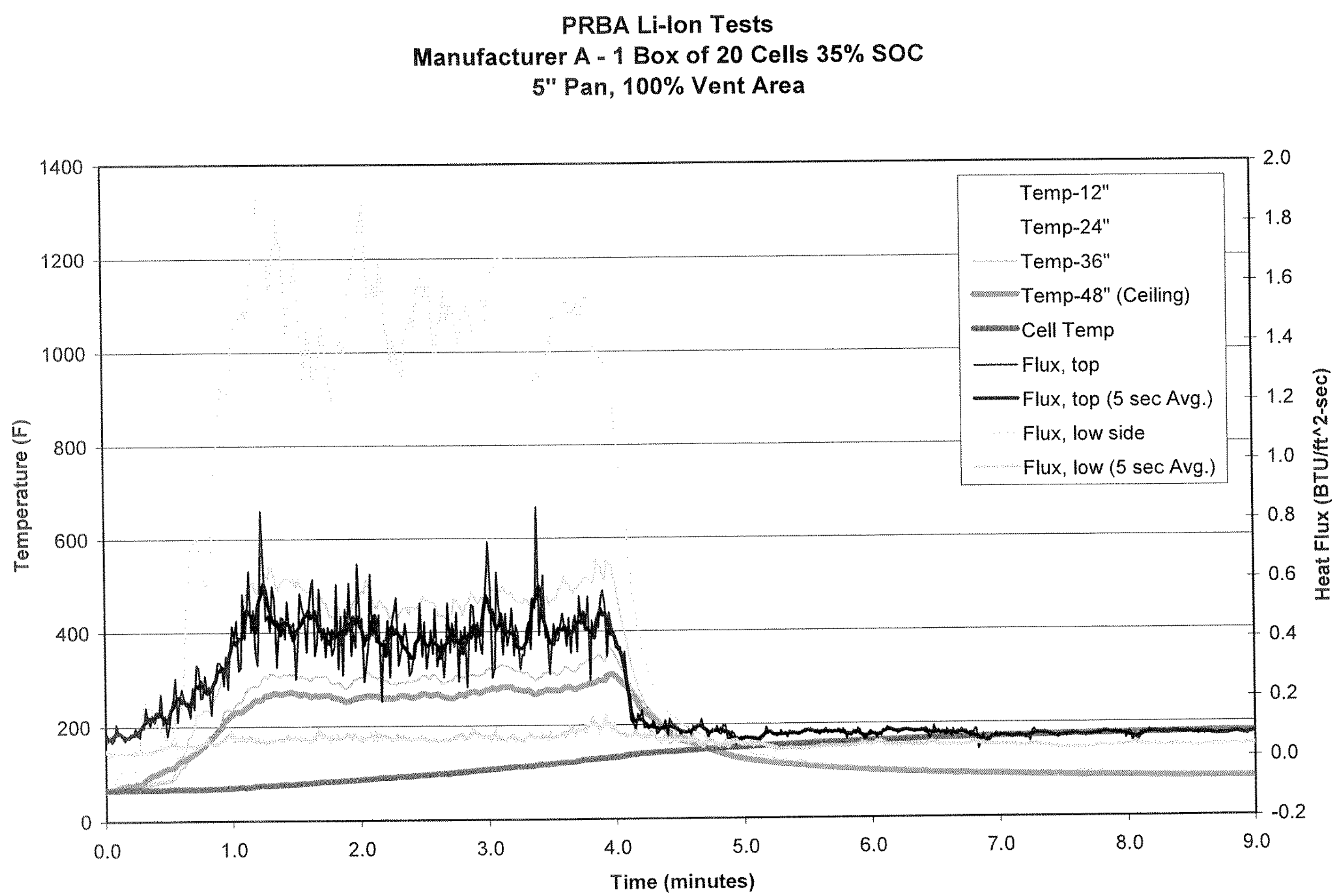

Figure B-17. Manufacturer A, 1 box containing 20 cells, 35% SOC.

Manufacturer A Tests

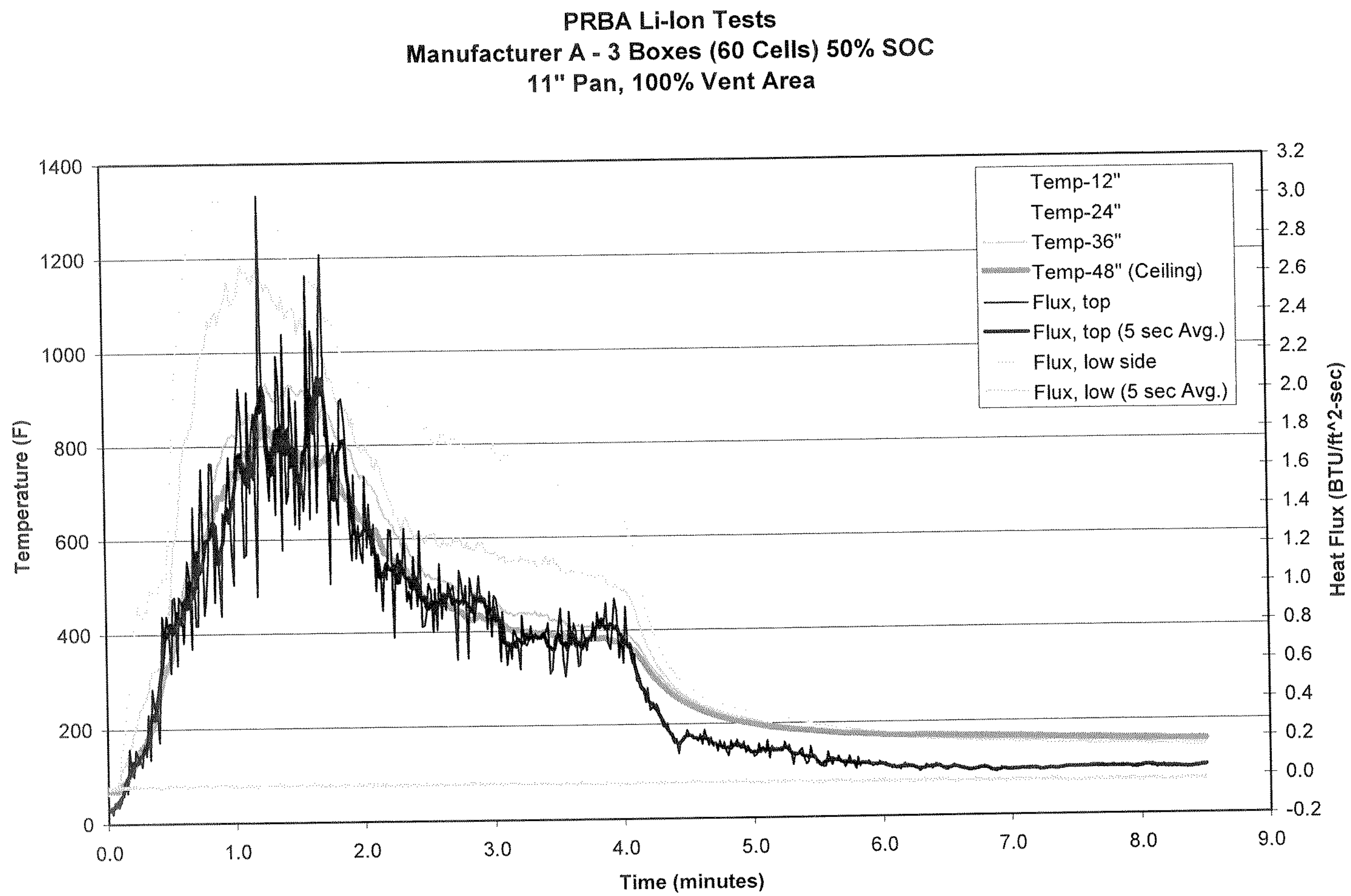

Figure B-18. Manufacturer A, 3 boxes of cells containing a total of 60 cells, 50% SOC.

Manufacturer A Tests

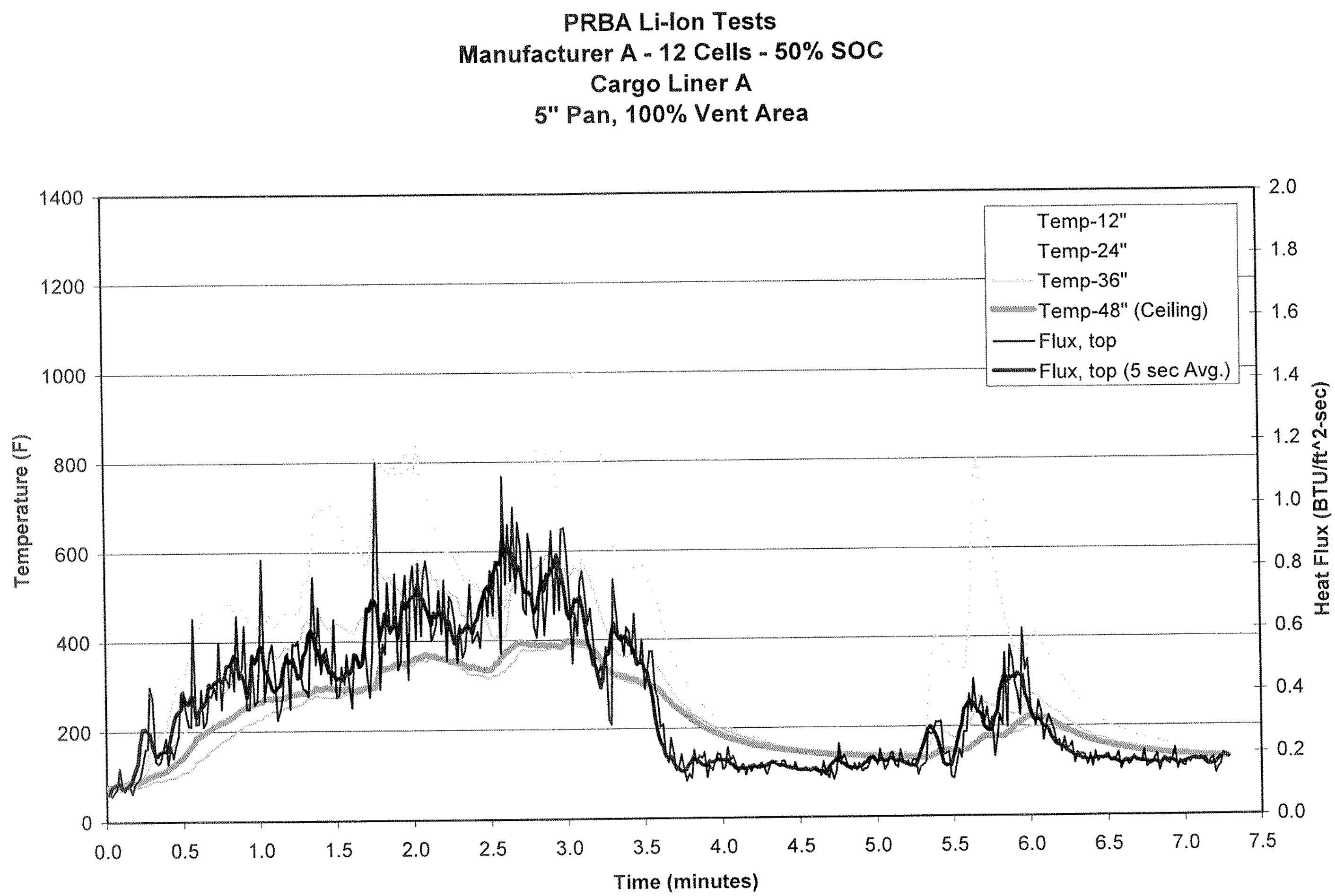

Figure B-19. Manufacturer A, 12 cells, 50% SOC, Cargo Liner A.

Manufacturer A Tests

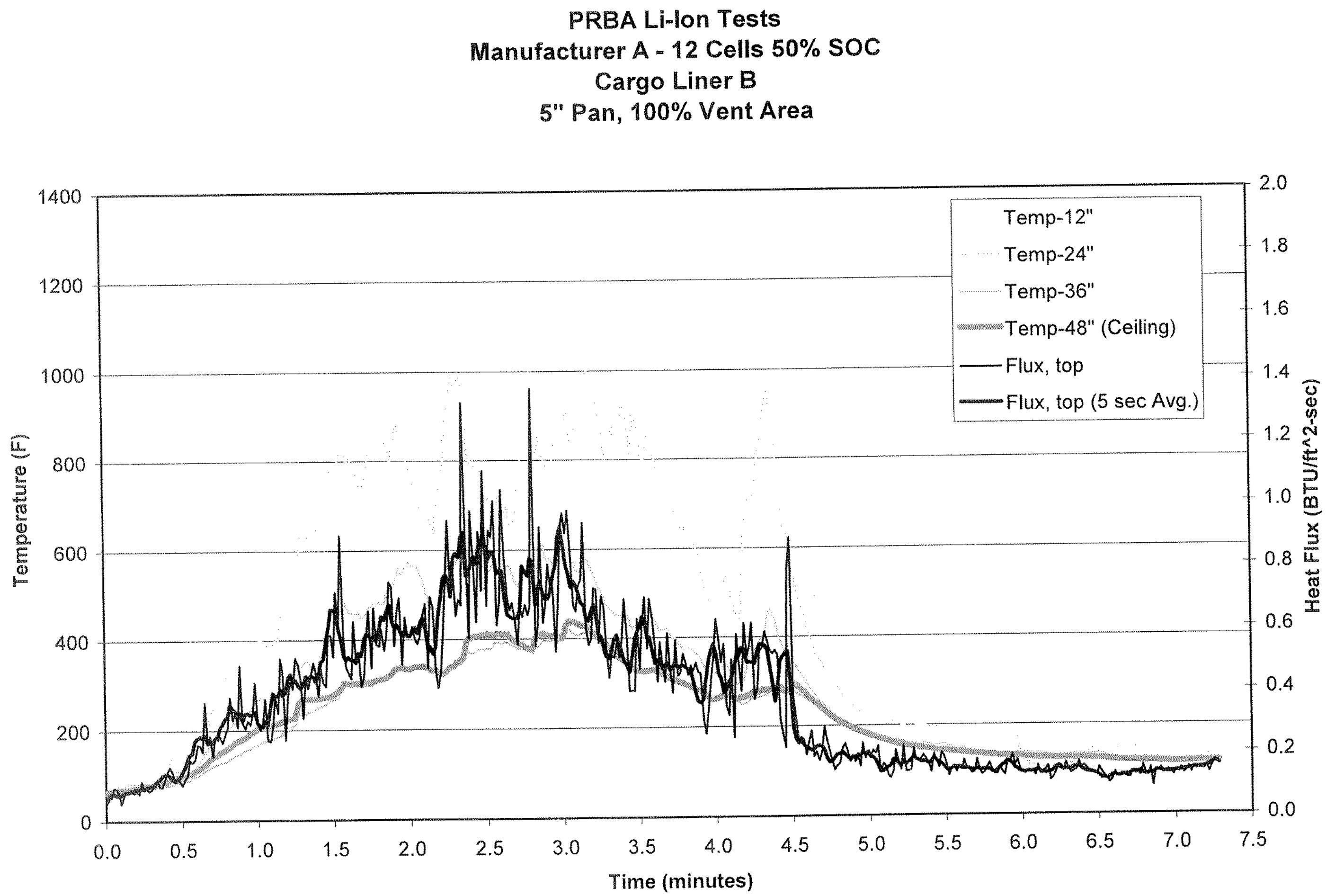

Figure B-20. Manufacturer A, 12 cells, 50% SOC, Cargo Liner B.

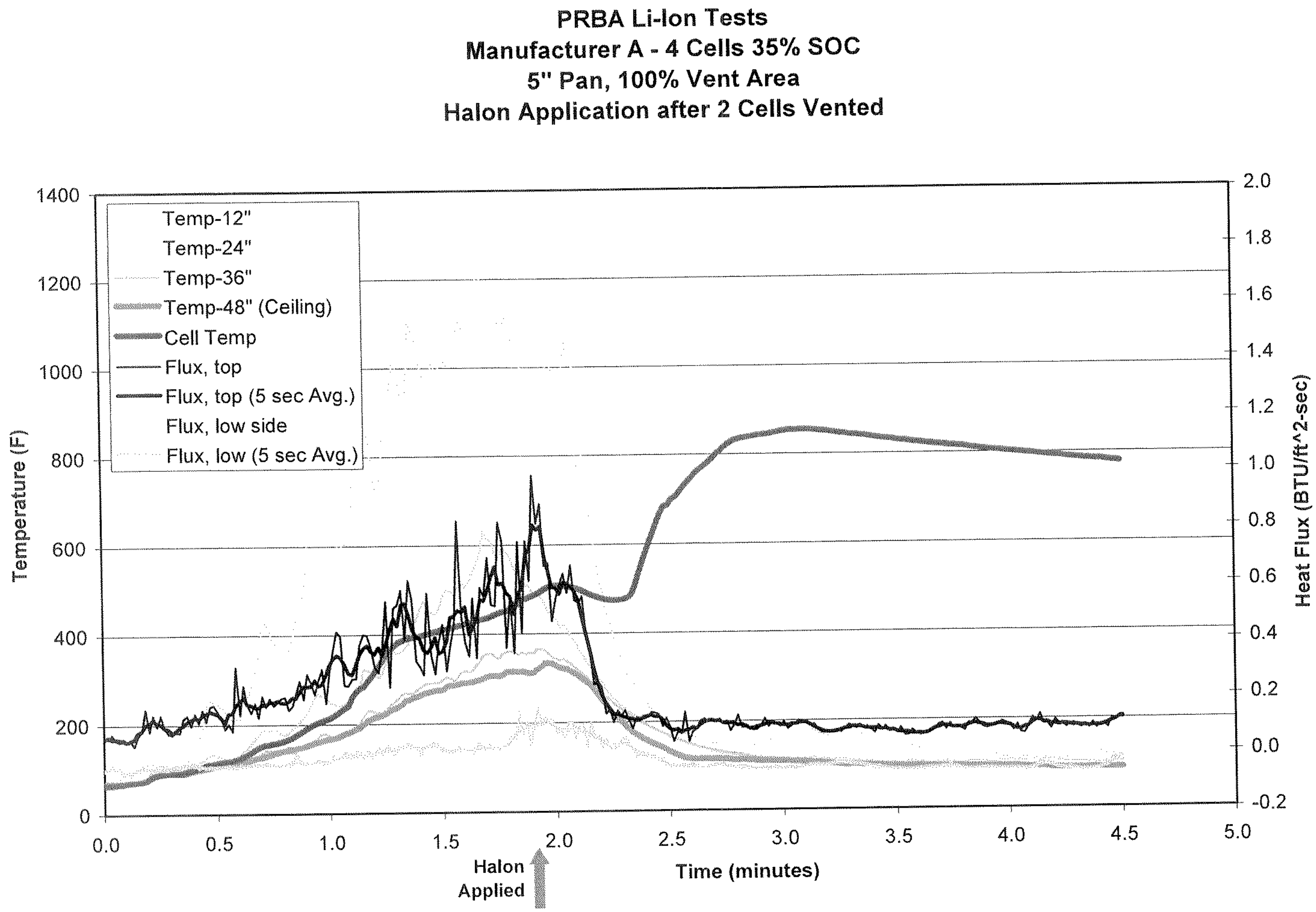

Figure B-21. Manufacturer A, 4 cells, 35% SOC, Halon 1301 applied after 2 cells vented (1:55).

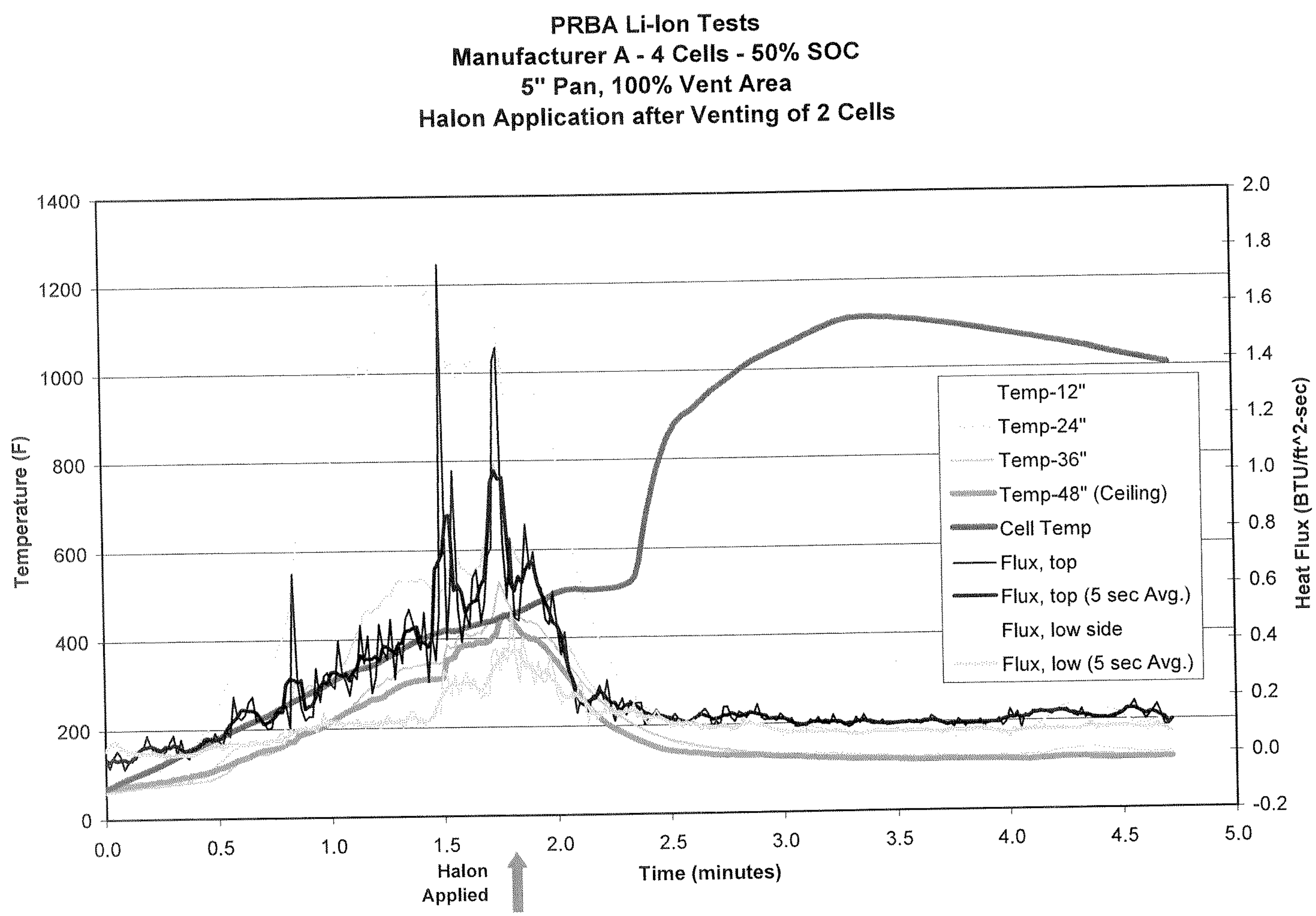

Figure B-22. Manufacturer A, 4 cells, 50% SOC, Halon 1301 applied after 2 cells vented (1:45).

Manufacturer A Tests

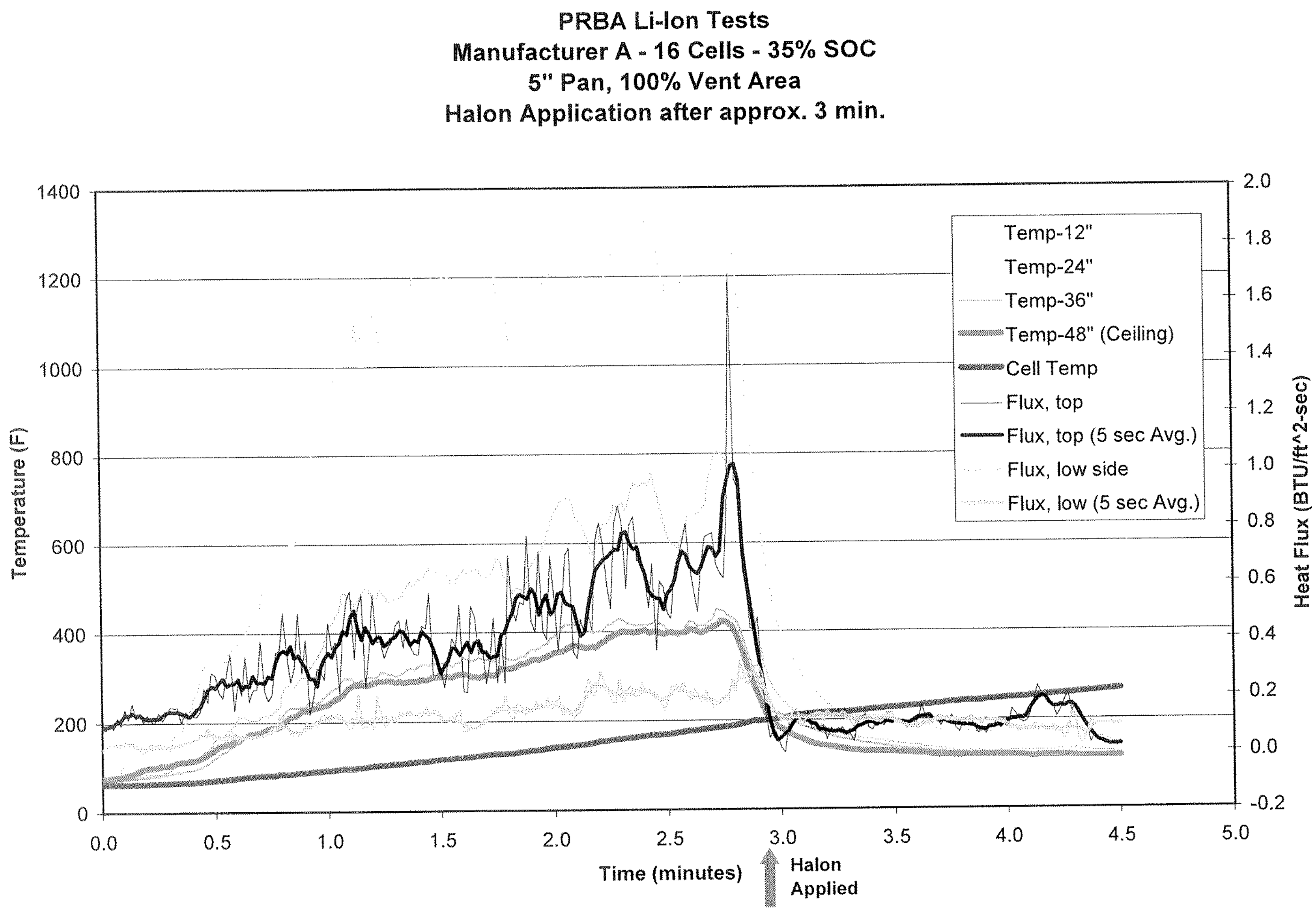

Figure B-23. Manufacturer A, 16 cells, 35% SOC, Halon 1301 applied after approximately 7 cells had vented (3:01).

Manufacturer A Tests

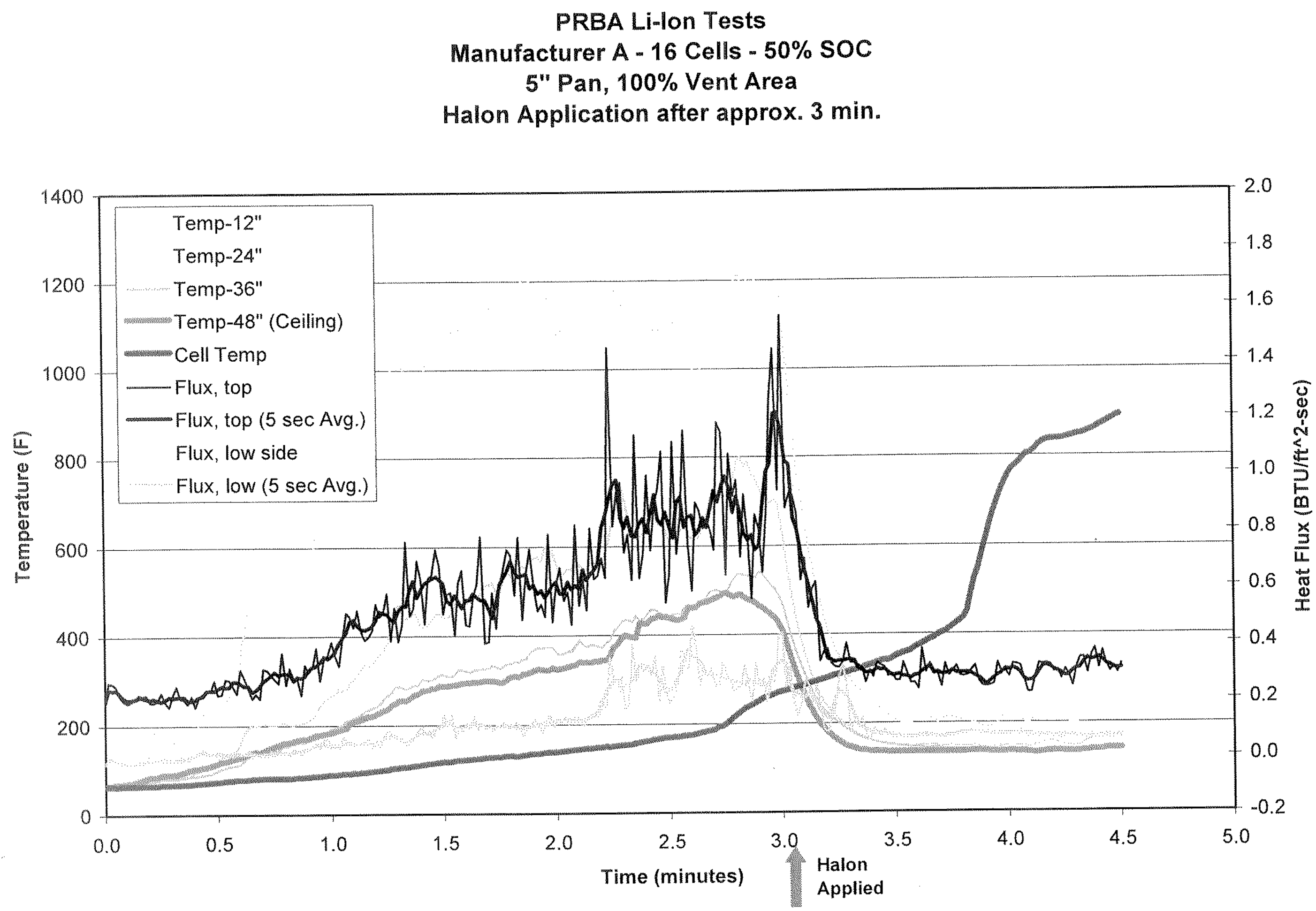

Figure B-24. Manufacturer A, 16 cells, 50% SOC, Halon 1301 applied after approximately 3 minutes.

Manufacturer A Tests

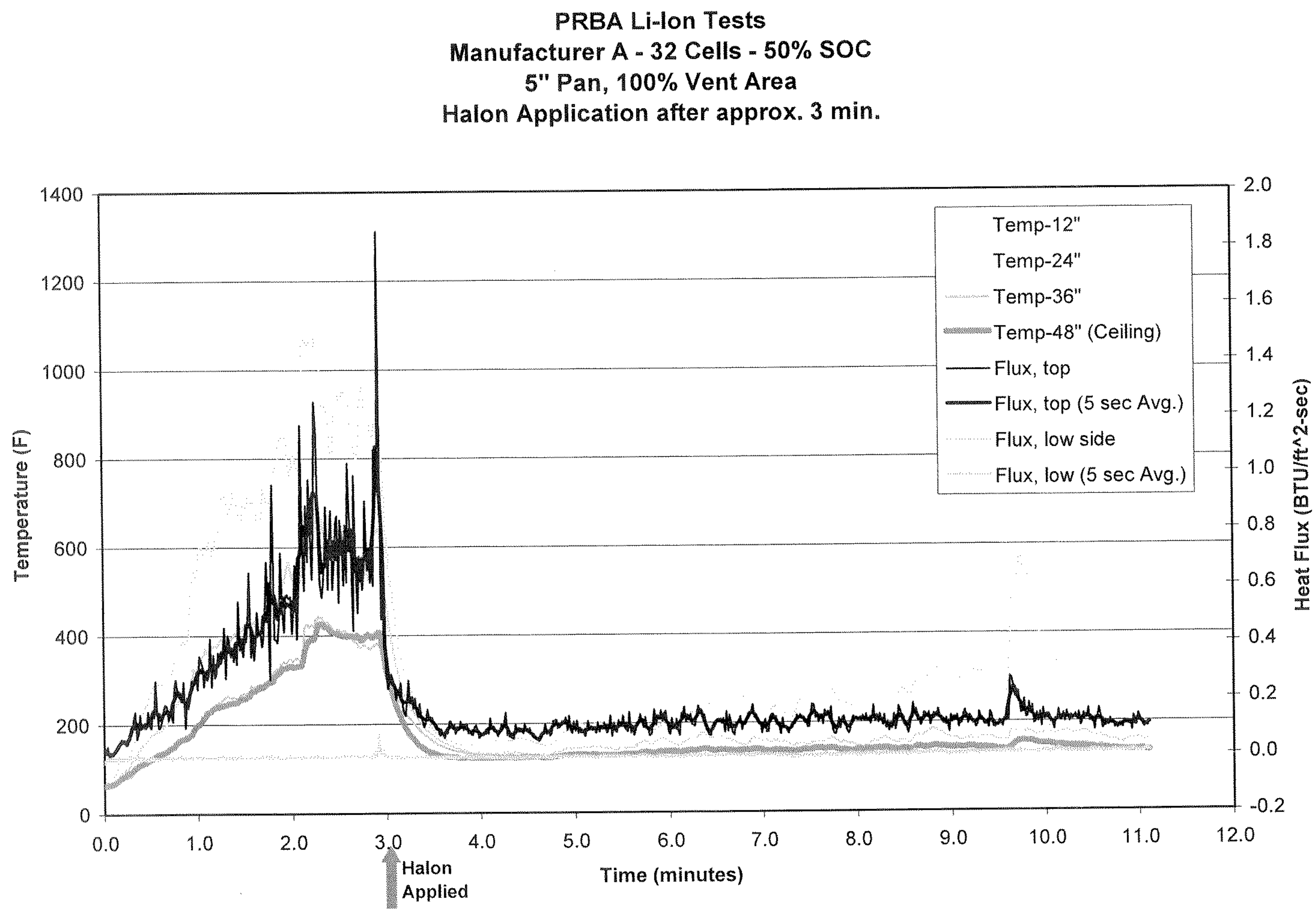

Figure B-25. Manufacturer A, 32 cells, 50% SOC, Halon 1301 applied at approximately 3 minutes.

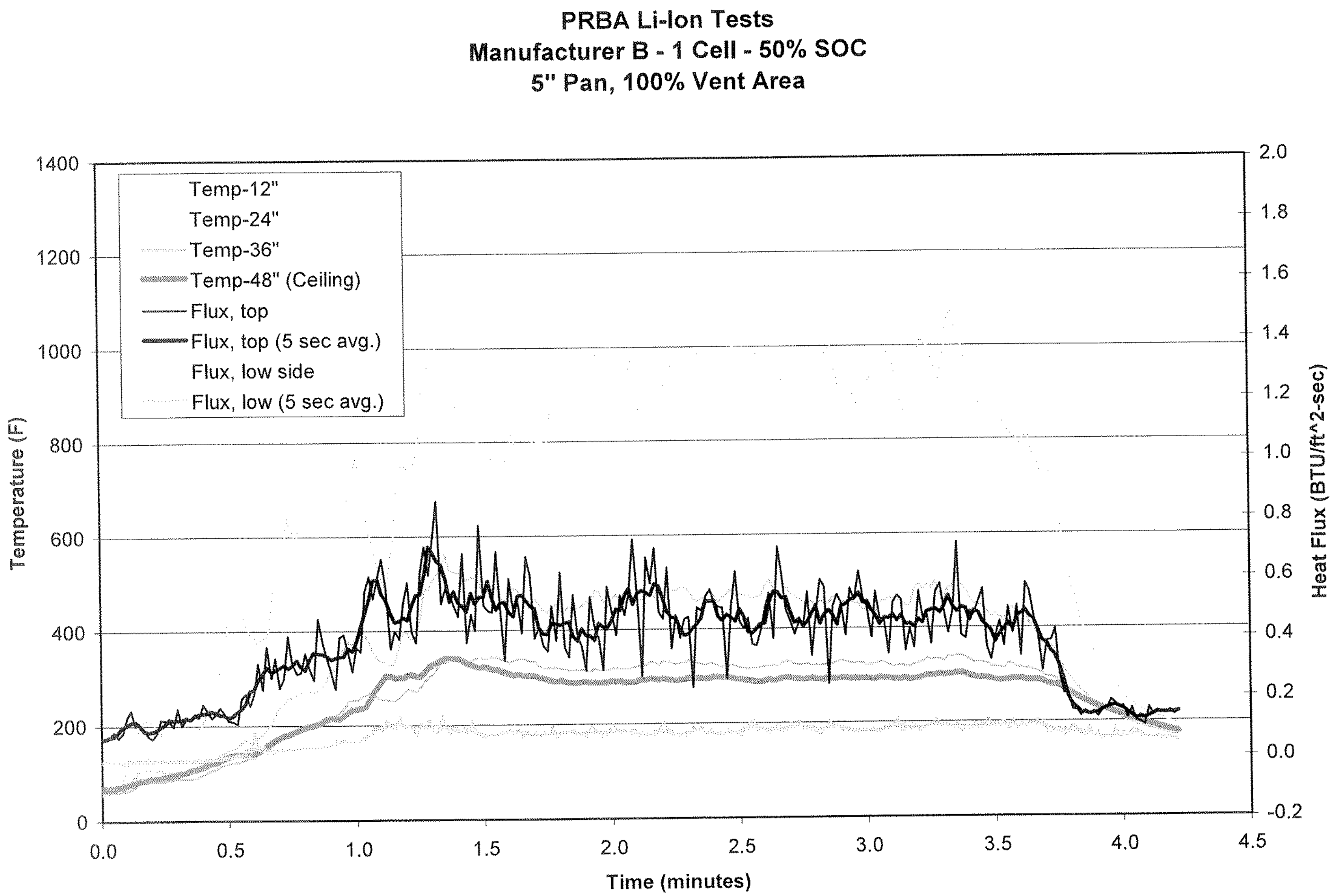

Figure B-26. Manufacturer B, single cell, 50% SOC.

Manufacturer B Tests

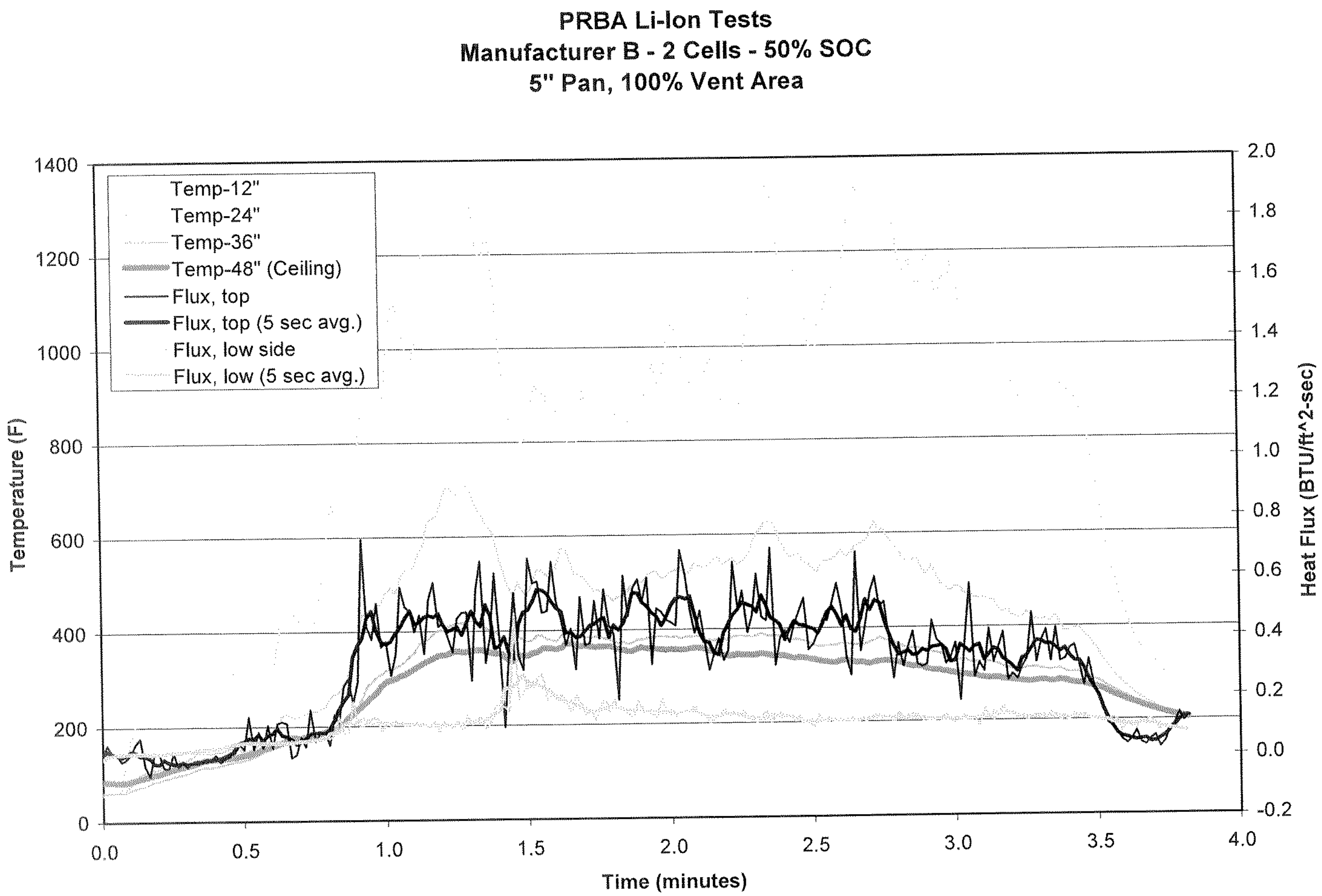

Figure B-27. Manufacturer B, 2 cells, 50% SOC.

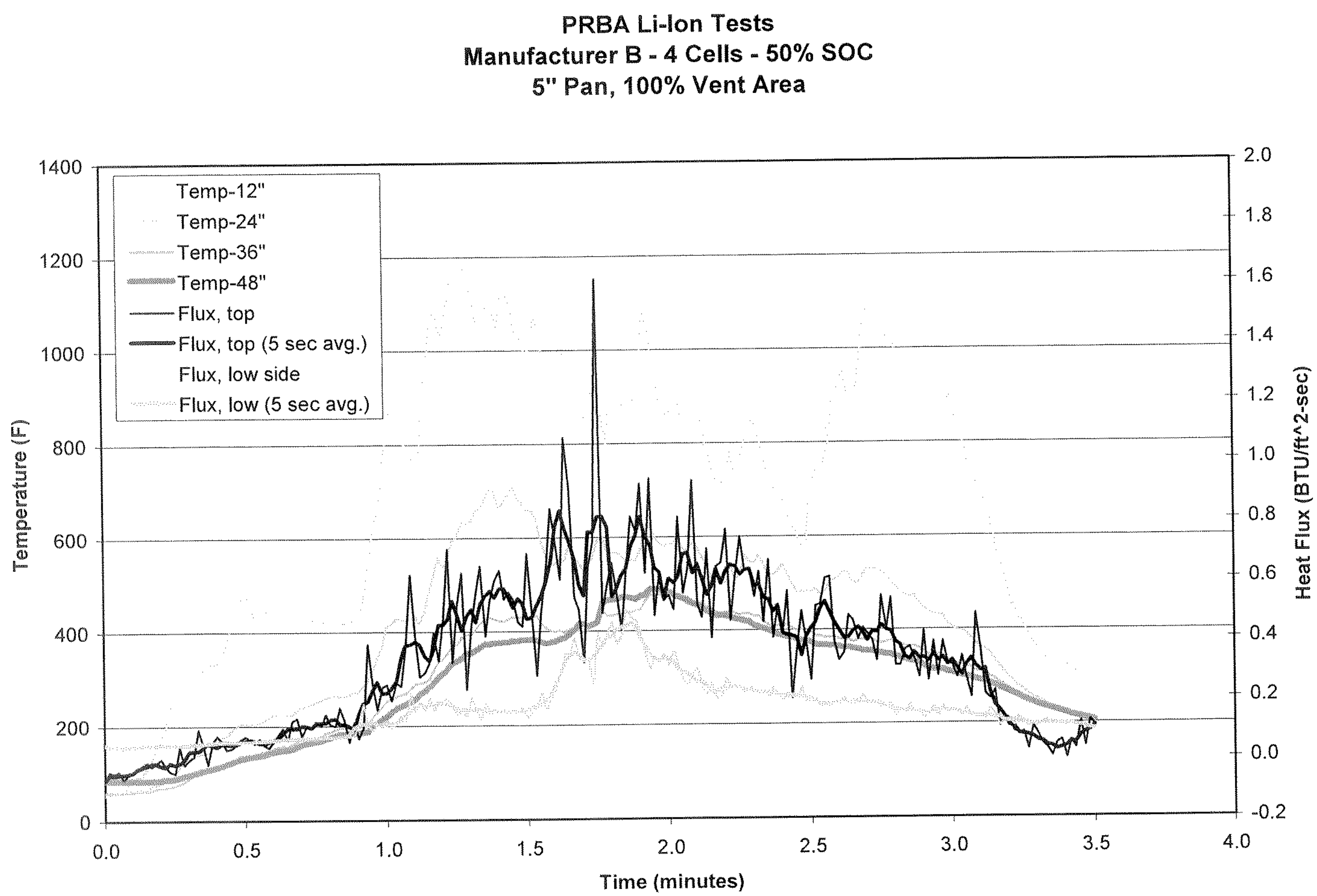

Figure B-28. Manufacturer B, 4 cells, 50% SOC.

Manufacturer B Tests

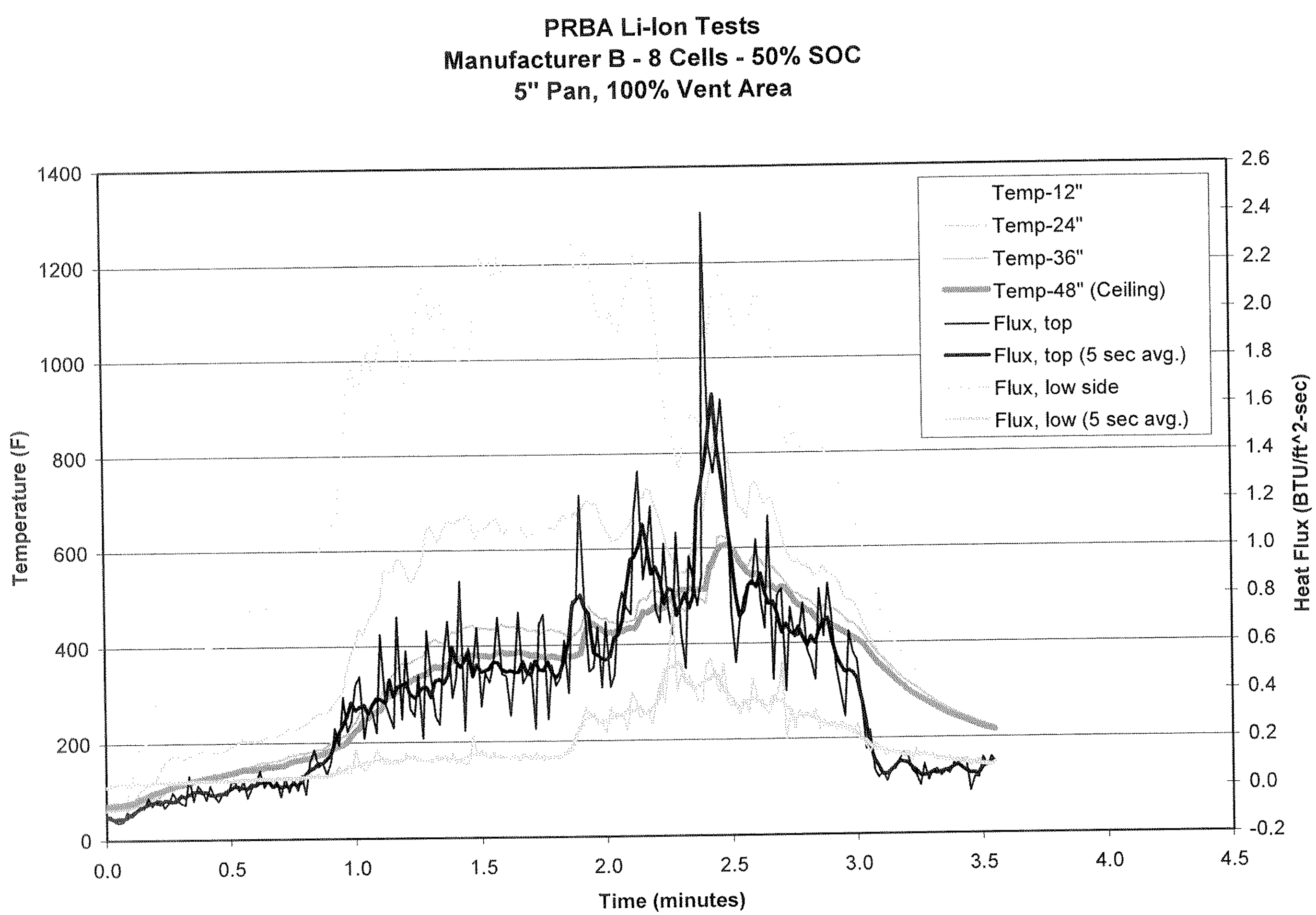

Figure B-29. Manufacturer B, 8 cells, 50% SOC.

Manufacturer B Tests

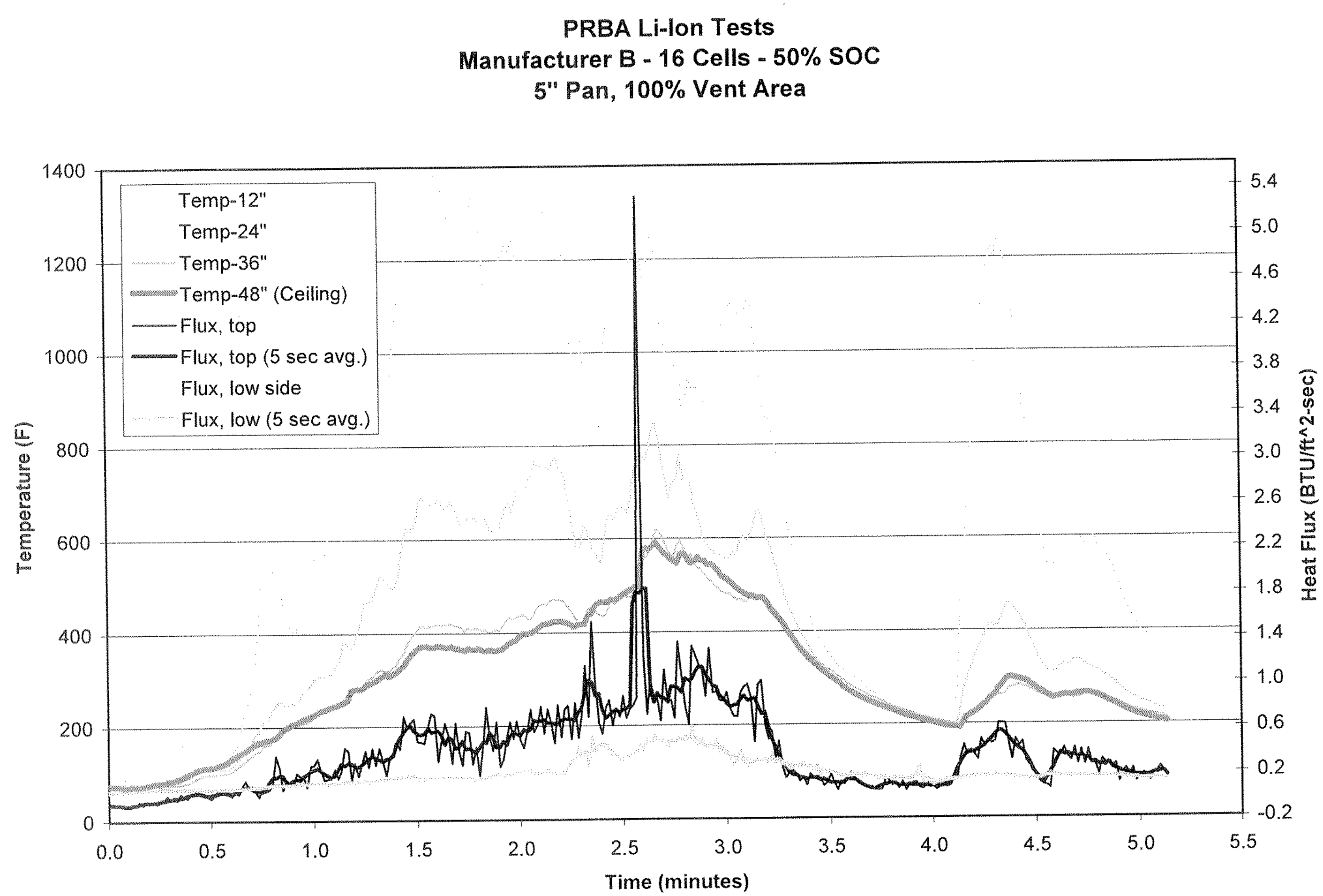

Figure B-30. Manufacturer B, 16 cells, 50% SOC.

Manufacturer B Tests

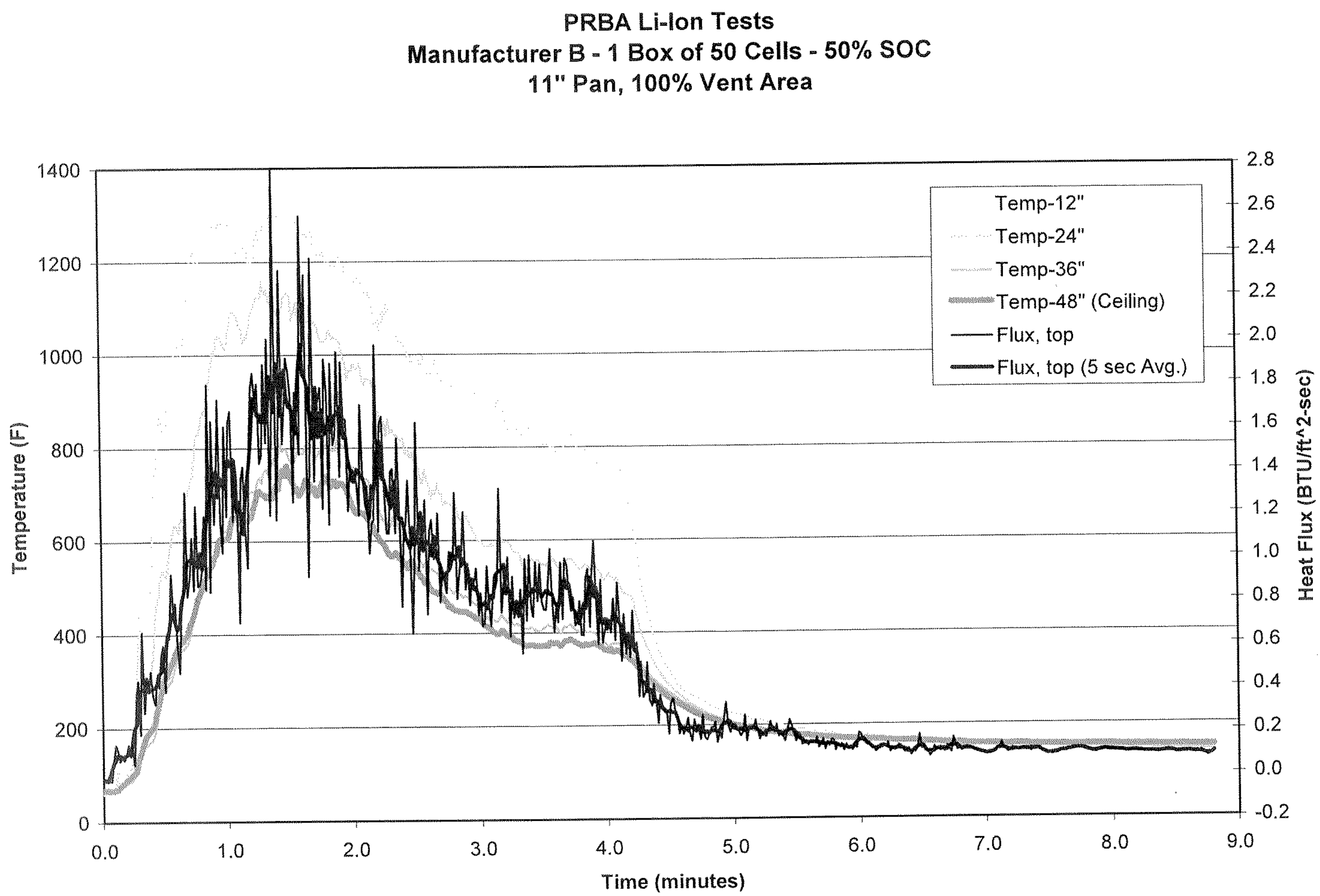

Figure B-31. Manufacturer B, 1 box containing 50 cells, 50% SOC.

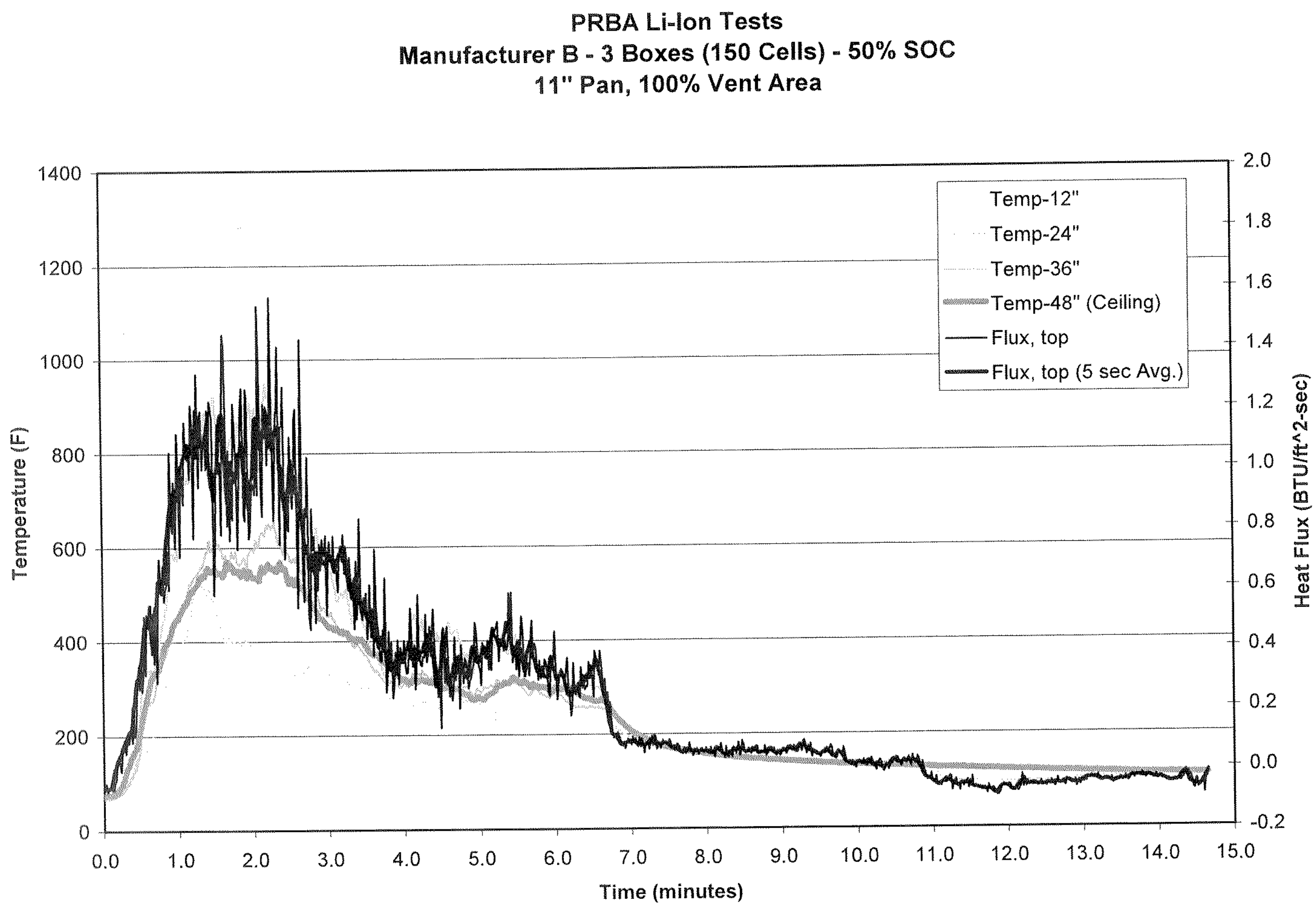

Figure B-32. Manufacturer B, 3 boxes containing a total of 150 cells, 50% SOC.

Manufacturer B Tests

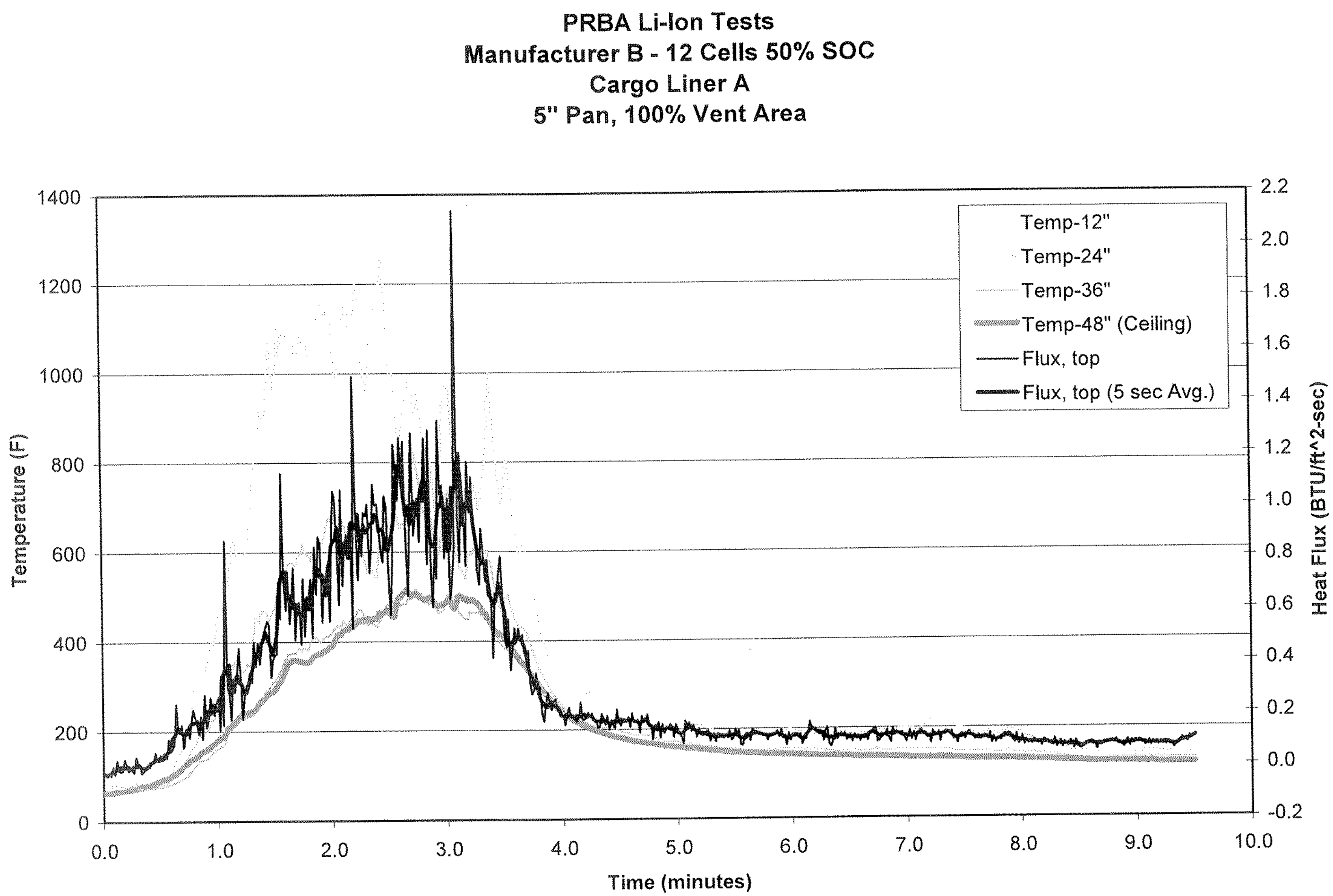

Figure B-33. Manufacturer B, 12 cells, 50% SOC, Cargo Liner A.

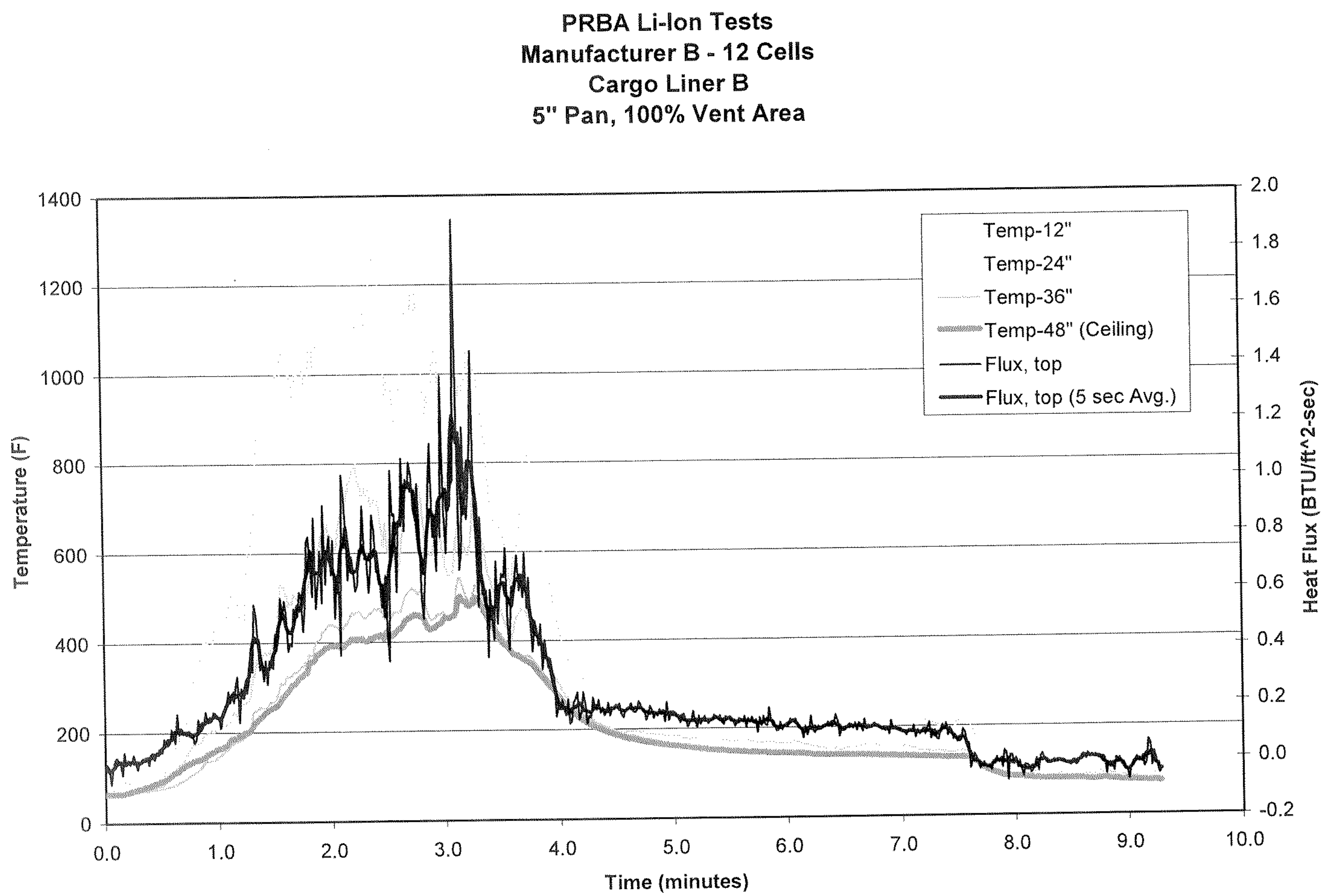

Figure B-34. Manufacturer B, 12 cells, 50% SOC, Cargo Liner B.

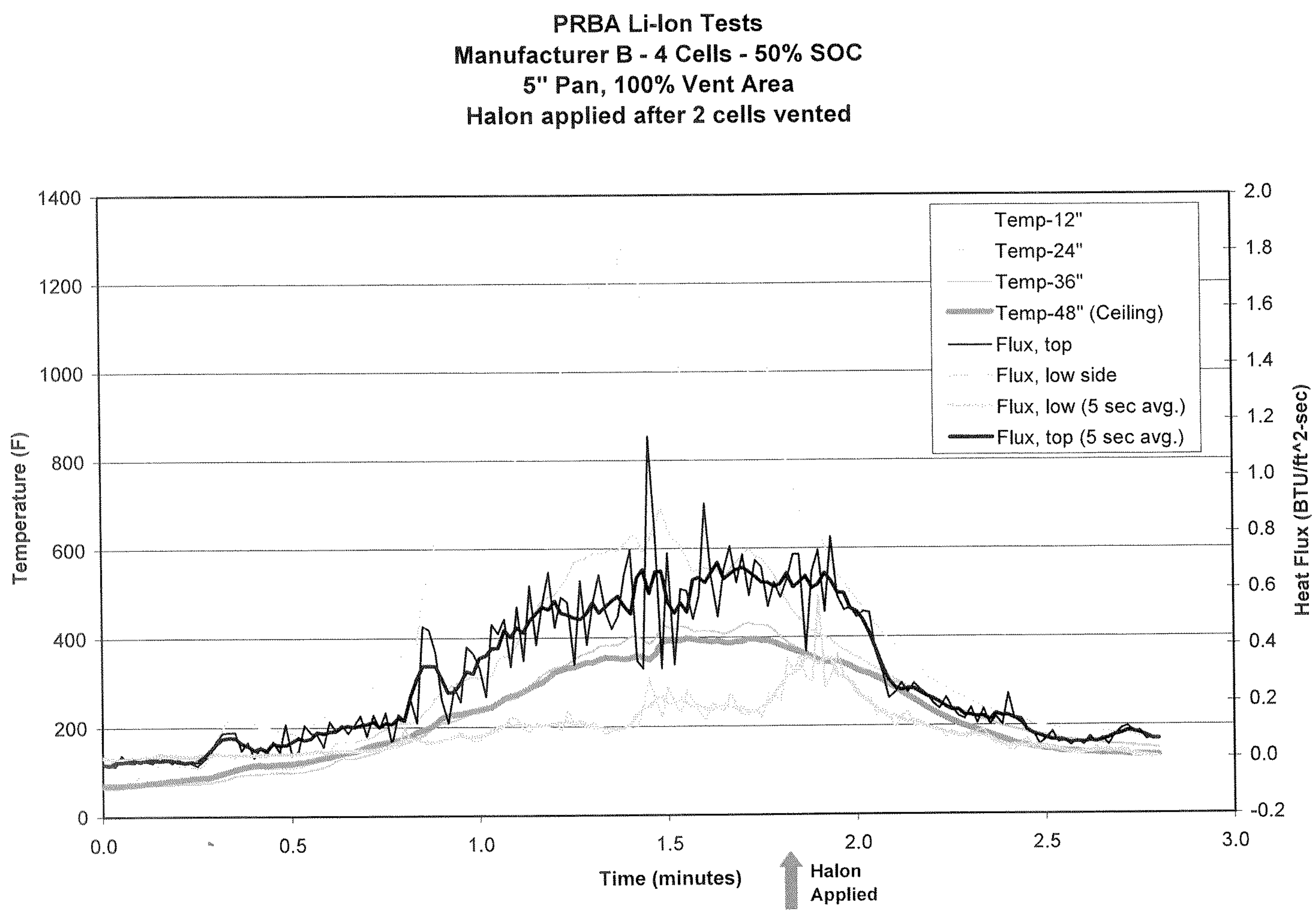

Figure B-35. Manufacturer B, 4 cells, 50% SOC, Halon 1301 applied after 2 cells vented (1:51).

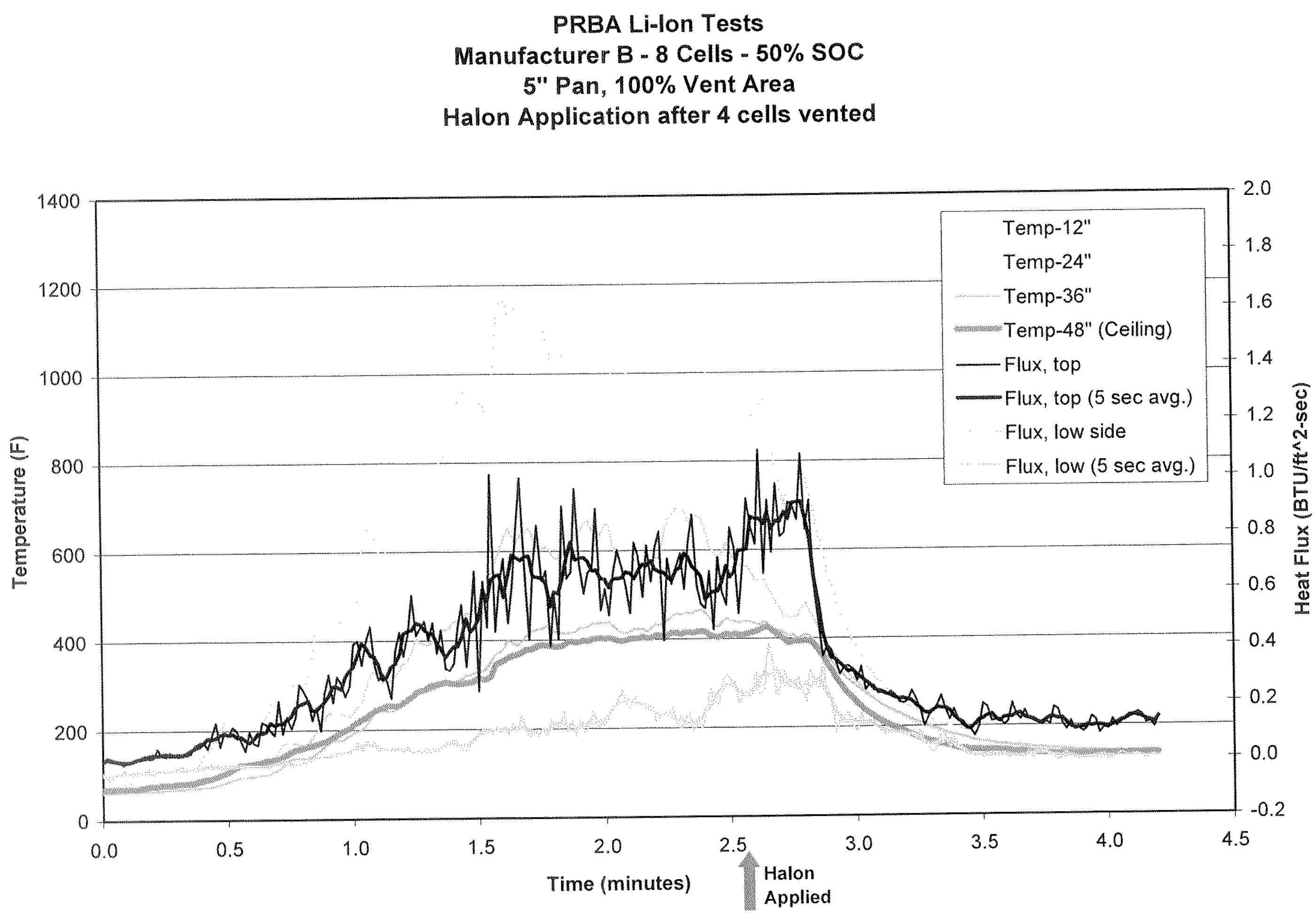

Figure B-36. Manufacturer B, 8 cells, 50% SOC, Halon 1301 applied after 4 cells vented (2:34).

Manufacturer B Tests

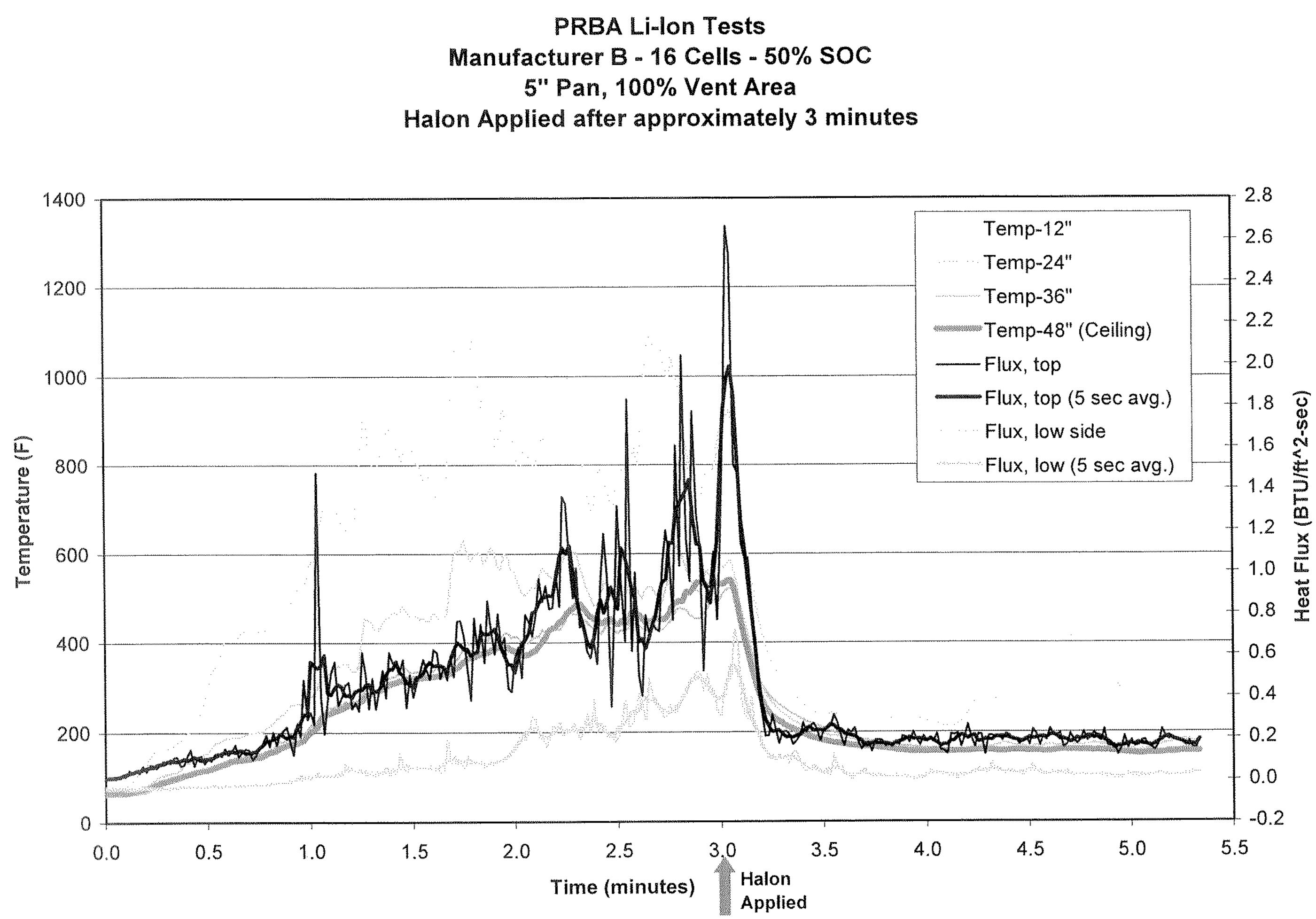

Figure B-37. Manufacturer B, 16 cells, 50% SOC, Halon 1301 applied after approximately 7 cells vented (3:00).

Manufacturer B Tests

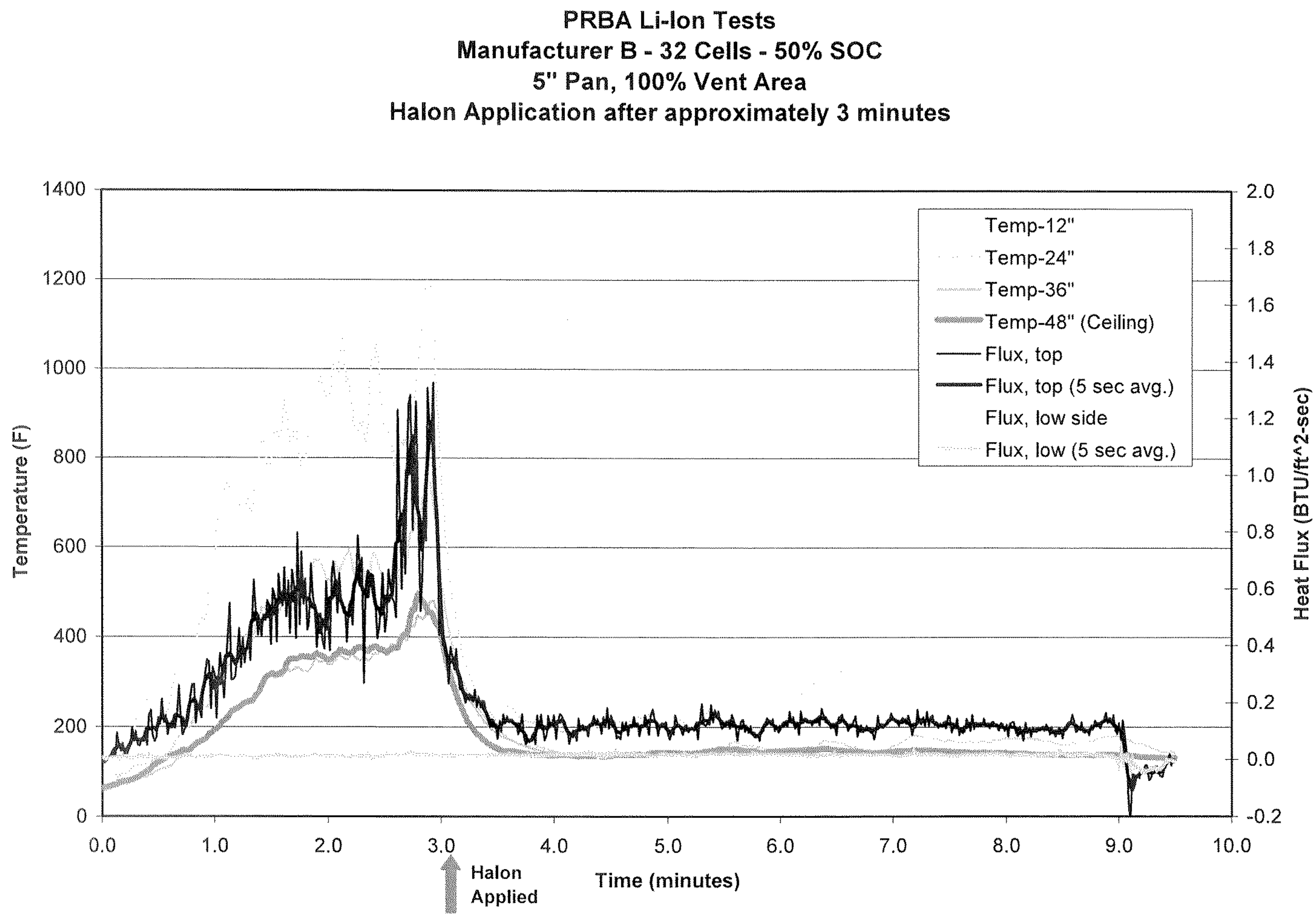

Figure B-38. Manufacturer B, 32 cells, 50% SOC, Halon 1301 applied after approximately 3 minutes.

Manufacturer C Tests

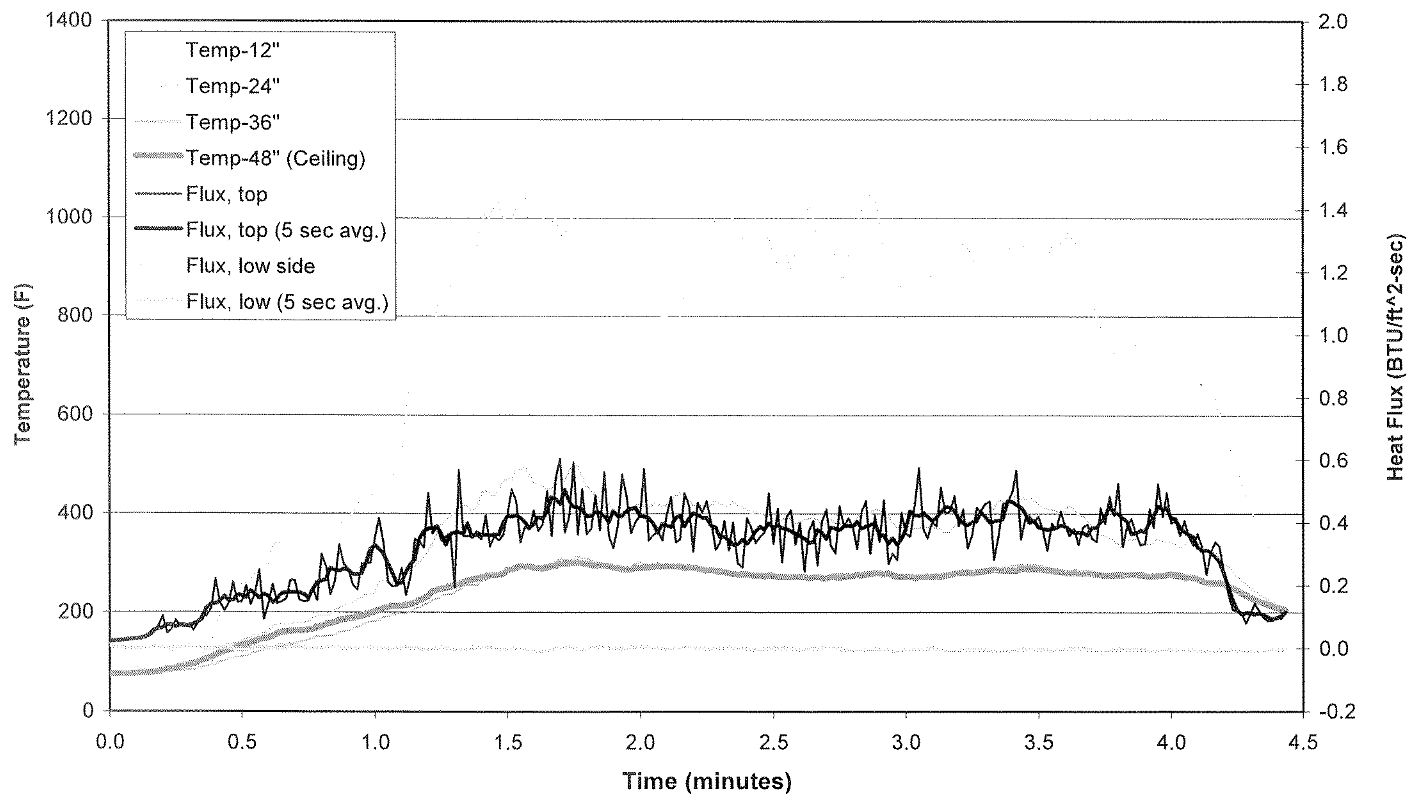

Figure B-39. Manufacturer C, 4 cells, 50% SOC.

Manufacturer C Tests

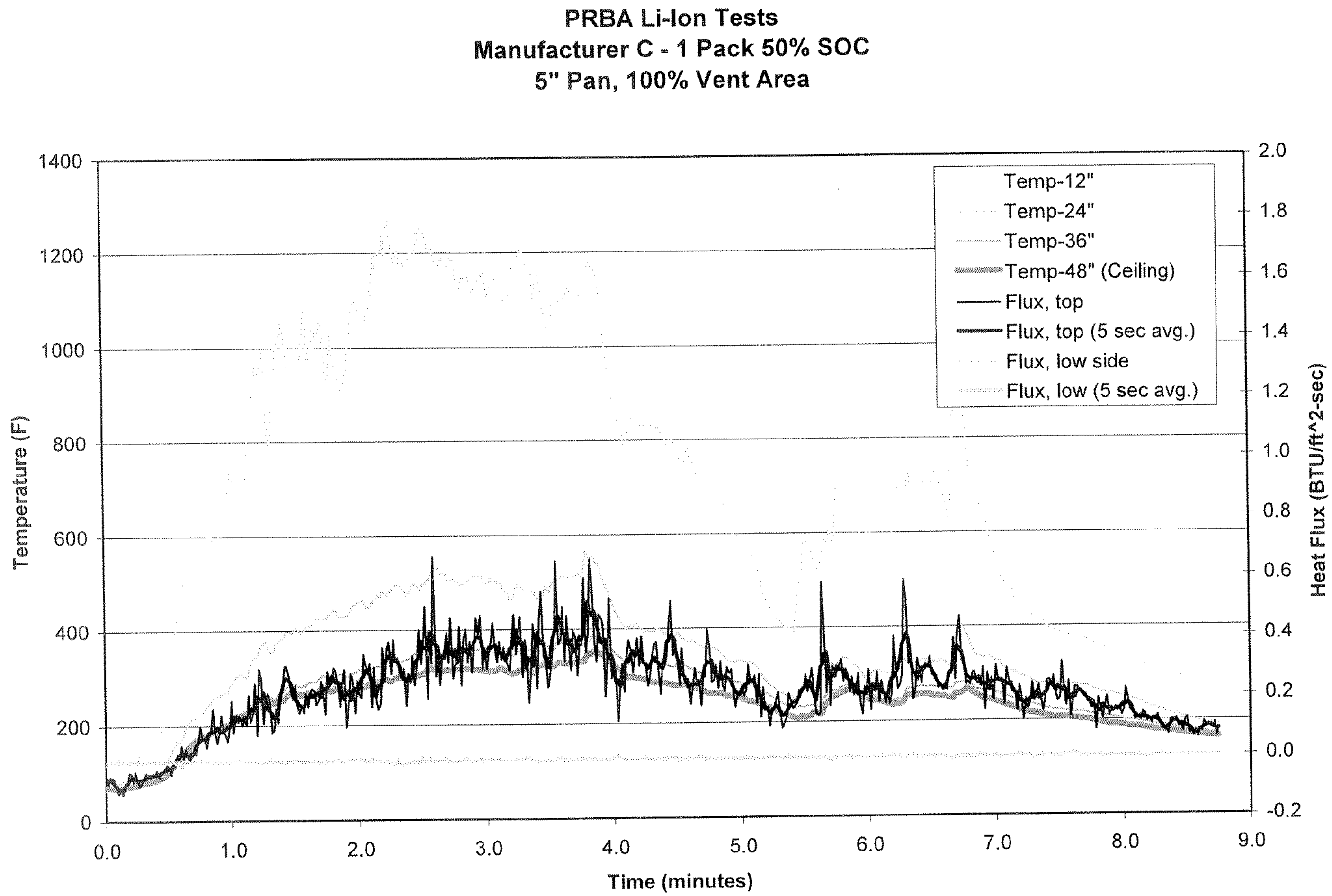

Figure B-40. Manufacturer C, one battery pack (8 cells), 50% SOC.

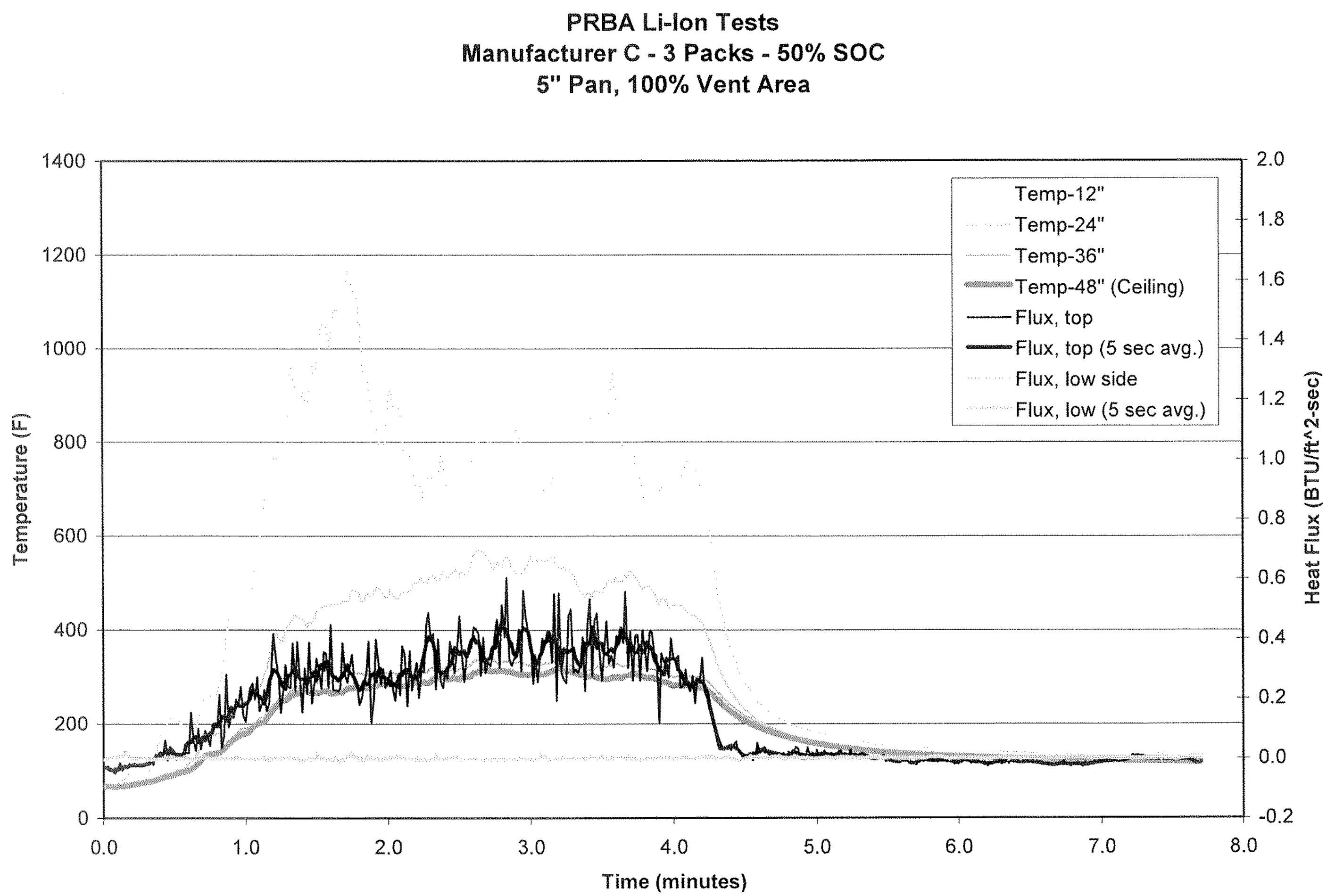

Figure B-41. Manufacturer C, 3 battery packs (total of 24 cells), 50% SOC.

Manufacturer C Tests

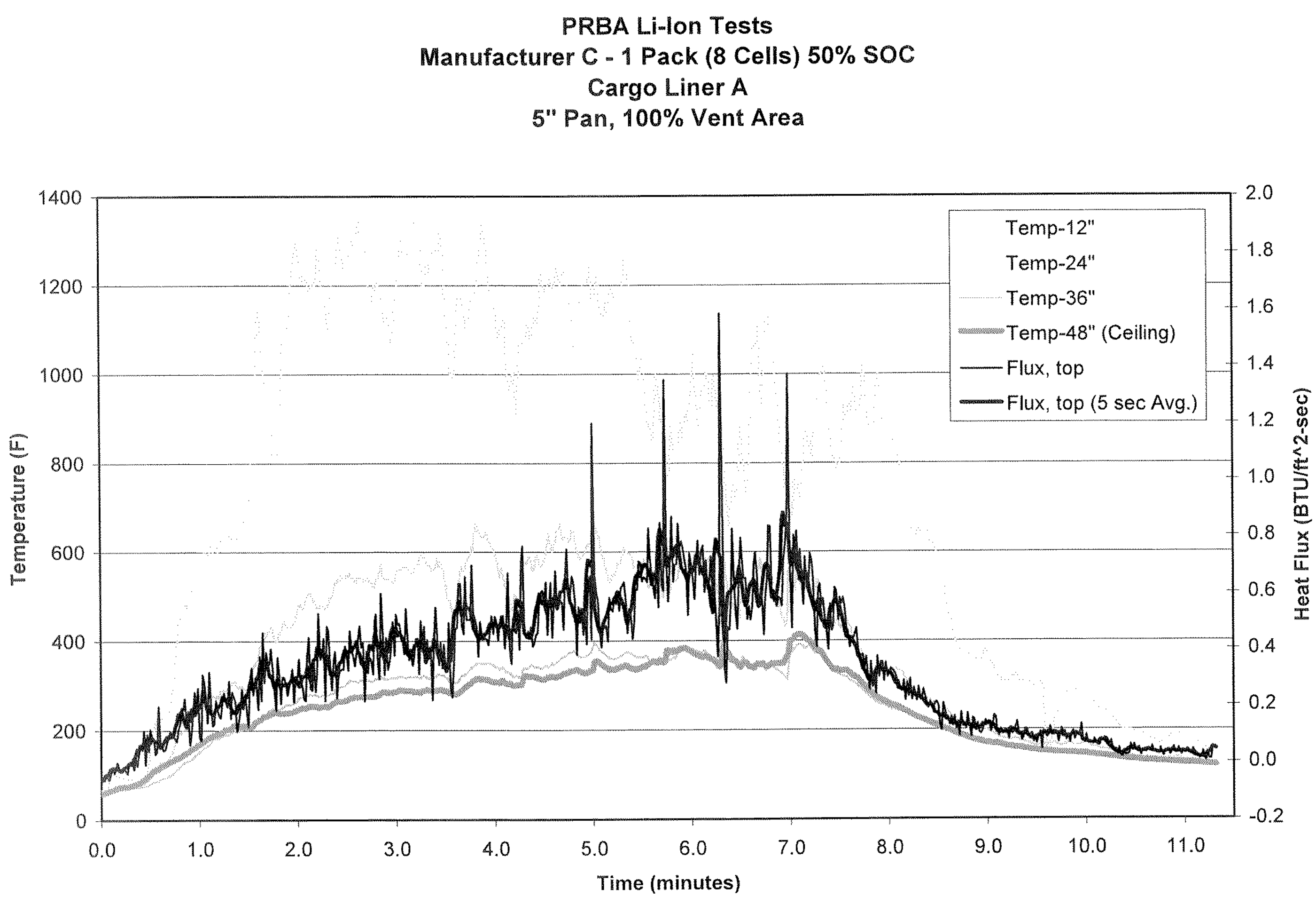

Figure B-42. Manufacturer C, one battery pack (8 cells), 50% SOC, Cargo Liner A.

Manufacturer C Tests

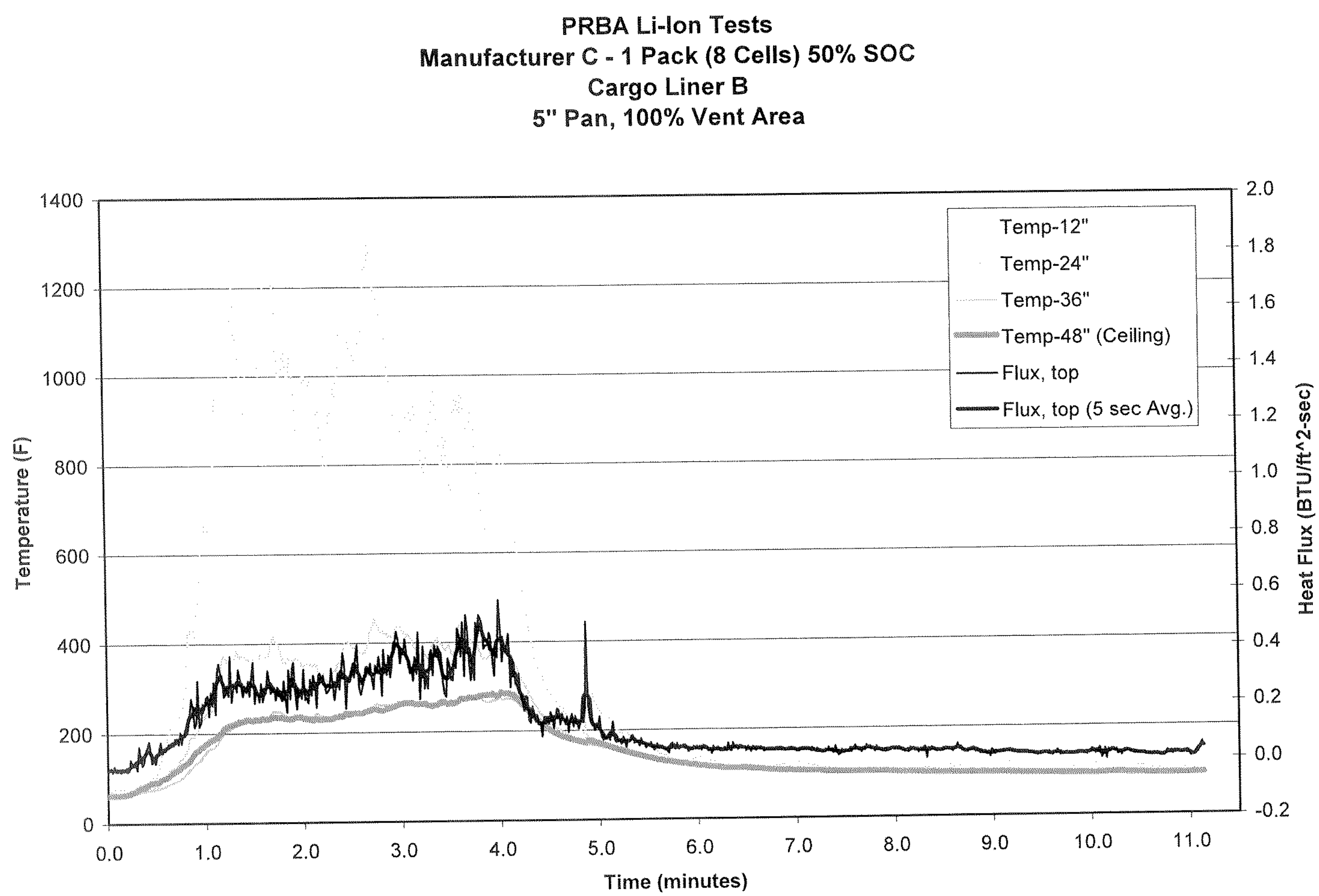

Figure B-43. Manufacturer C, one battery pack (8 cells), 50% SOC, Cargo Liner B.

Manufacturer C Tests

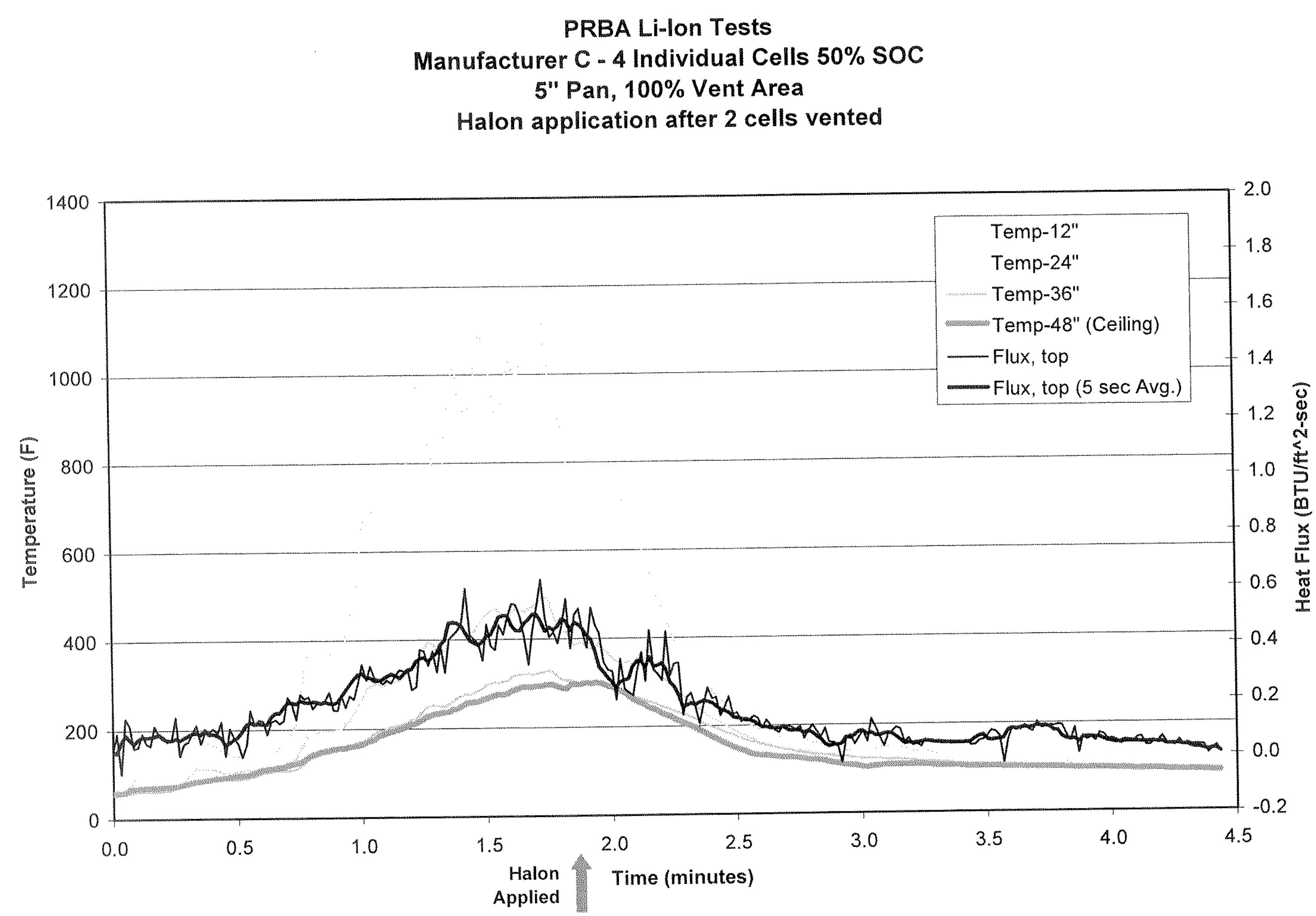

Figure B-44. Manufacturer C, 4 cells, 50% SOC, Halon 1301 applied after 2 cells vented (1:52).

Manufacturer C Tests

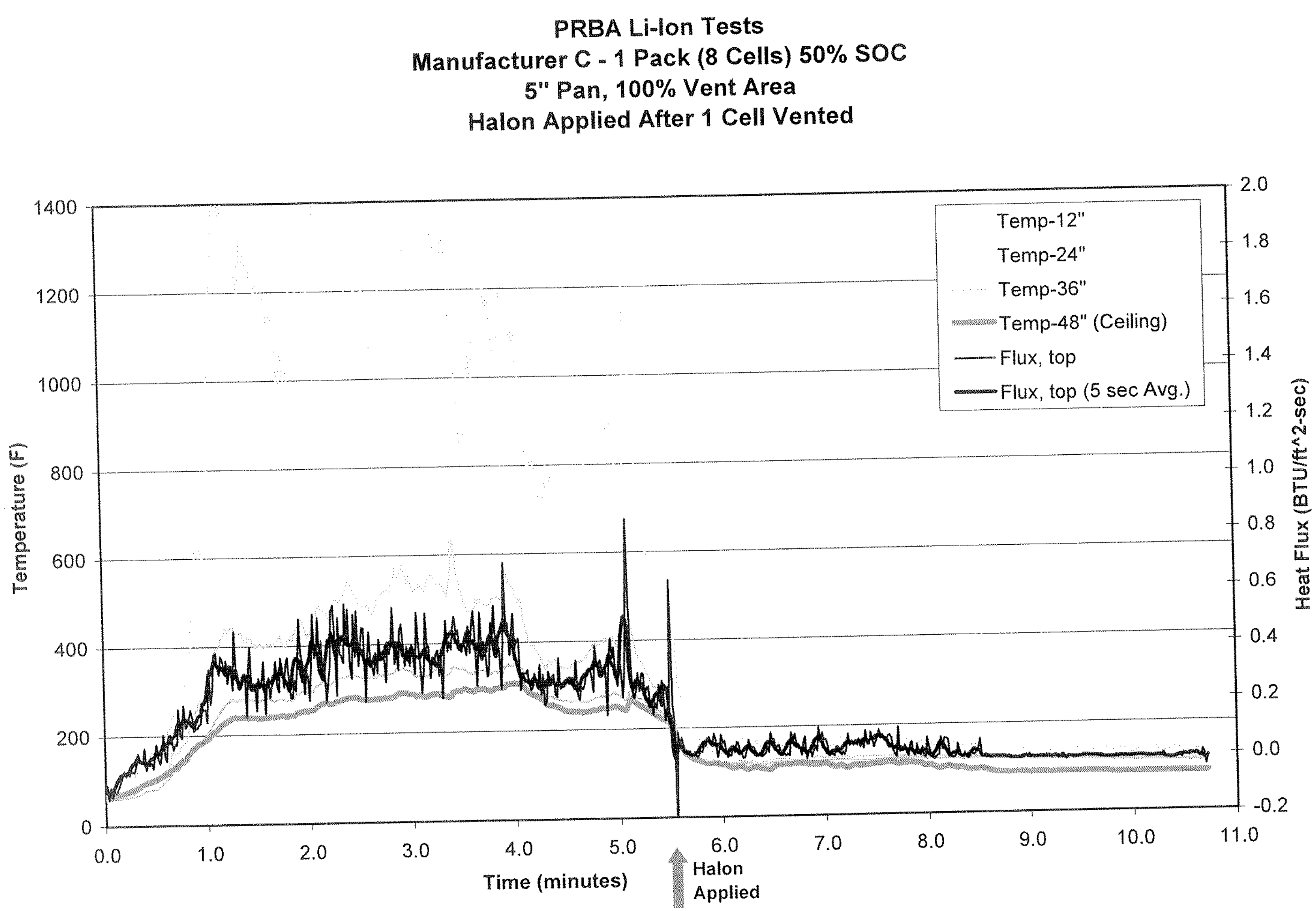

Figure B-45. Manufacturer C, one battery pack (8 cells), 50% SOC, Halon 1301 applied after an observed cell venting (5:38).

Appendix C

Post Testing Photographs

Appendix C   Post Testing Photographs

Figure C-1.   Manufacturer A Packaging Material (empty cardboard box).

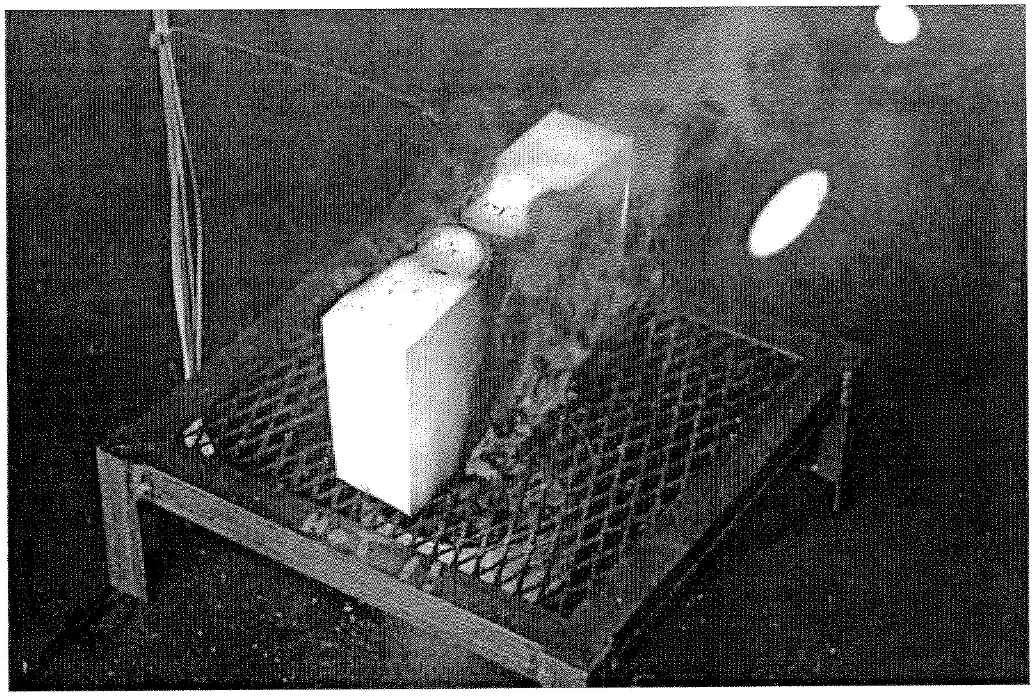

Figure C-2. Common box of facial tissue.

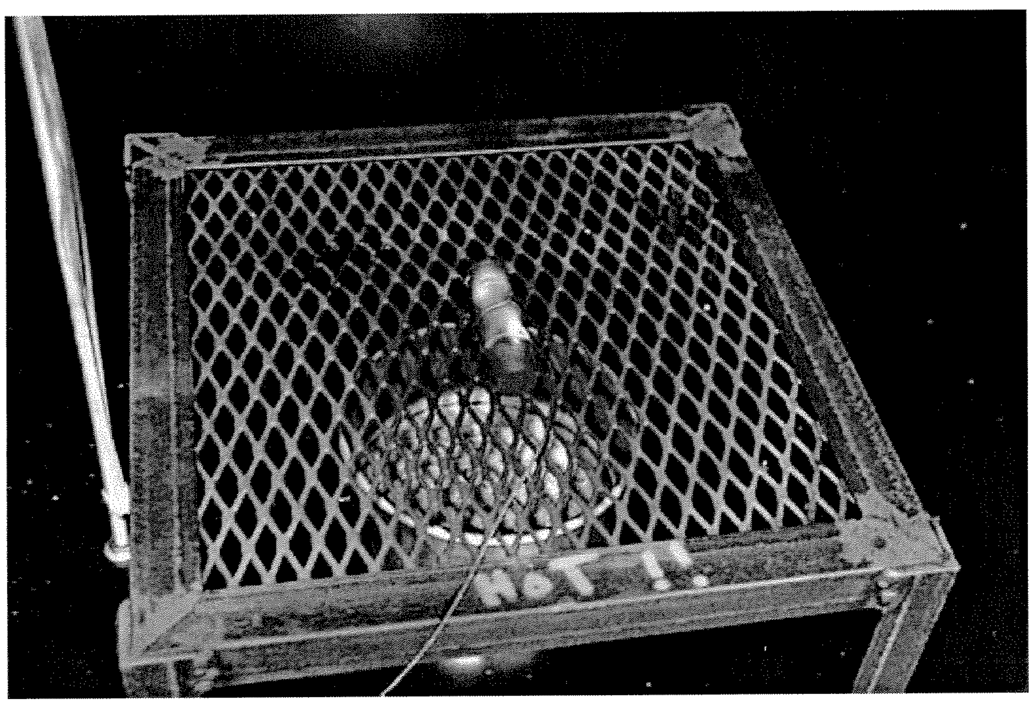

Figure C-3. Manufacturer A, single cell, 35% SOC, 5" pan.

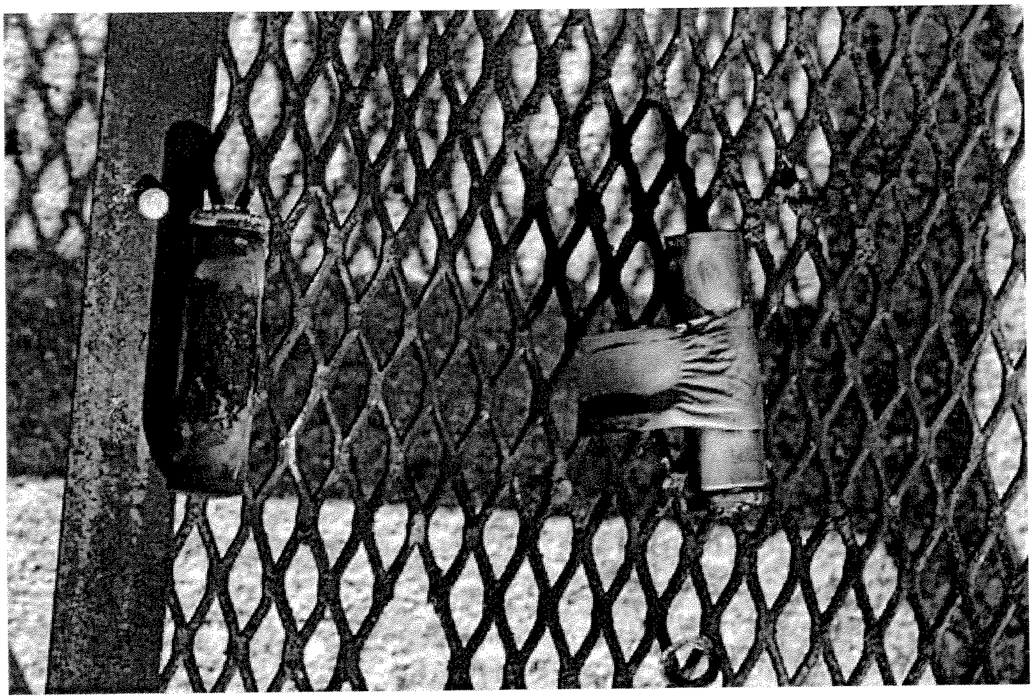

Figure C-4. Manufacturer A, 2 cells, 50% SOC, 5" pan.

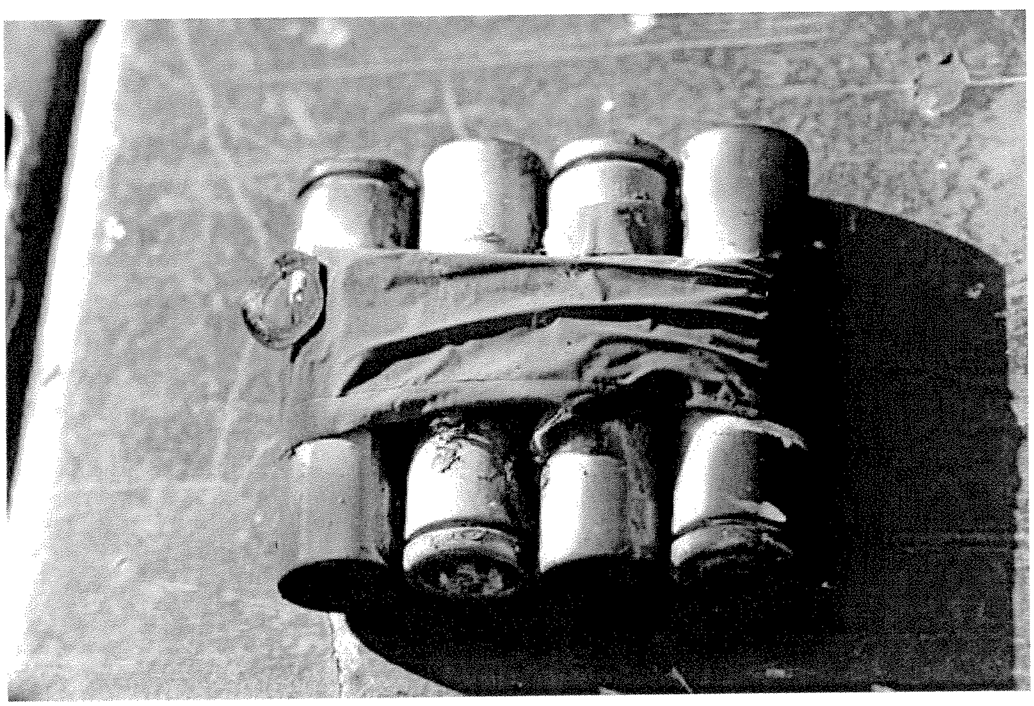

Figure C-5. Manufacturer A, 4 cells, 50% SOC, 5" pan.

Figure C-6. Manufacturer A, 8 cells, 50% SOC, 5" pan.

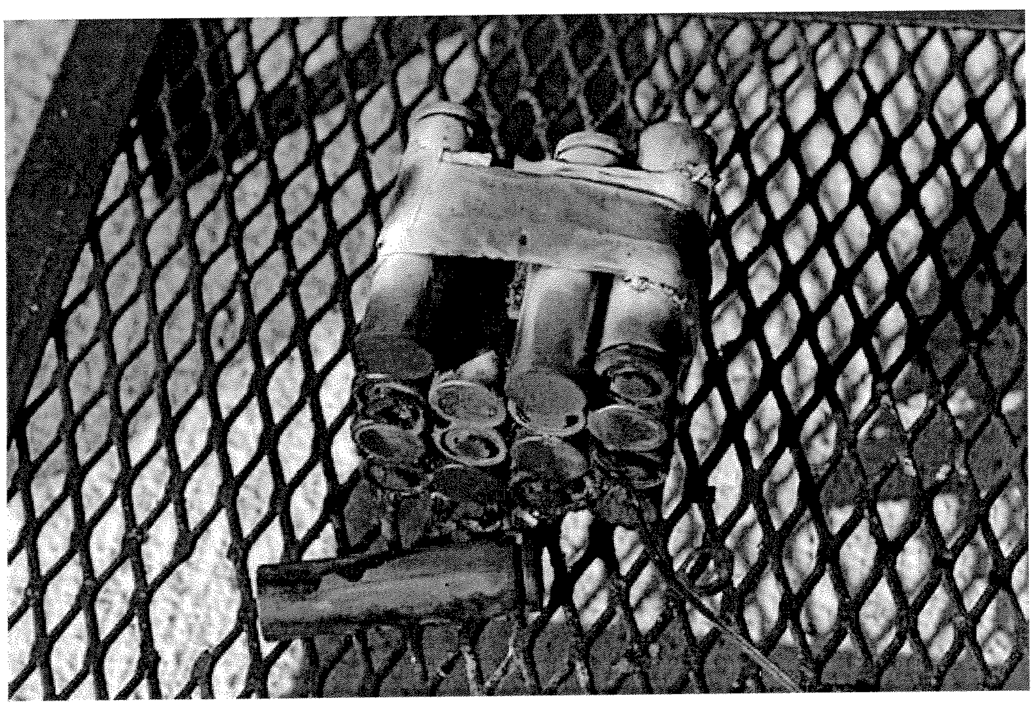

Figure C-7. Manufacturer A, 16 cells, 35% SOC, 5" pan.

Figure C-8. Manufacturer A, 16 cells, 50% SOC, 5" pan.

Figure C-9. Manufacturer A, 1 box with 20 cells, 35% SOC, 5" pan.

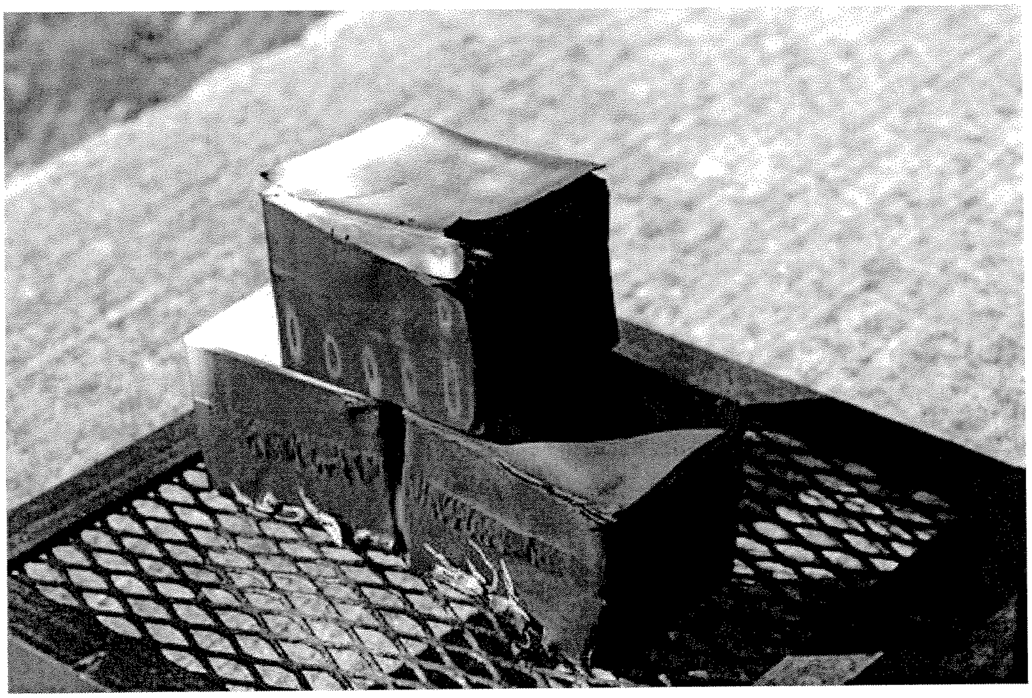

Figure C-10. Manufacturer A, 3 boxes with 20 cells each, 50% SOC, 11" pan.

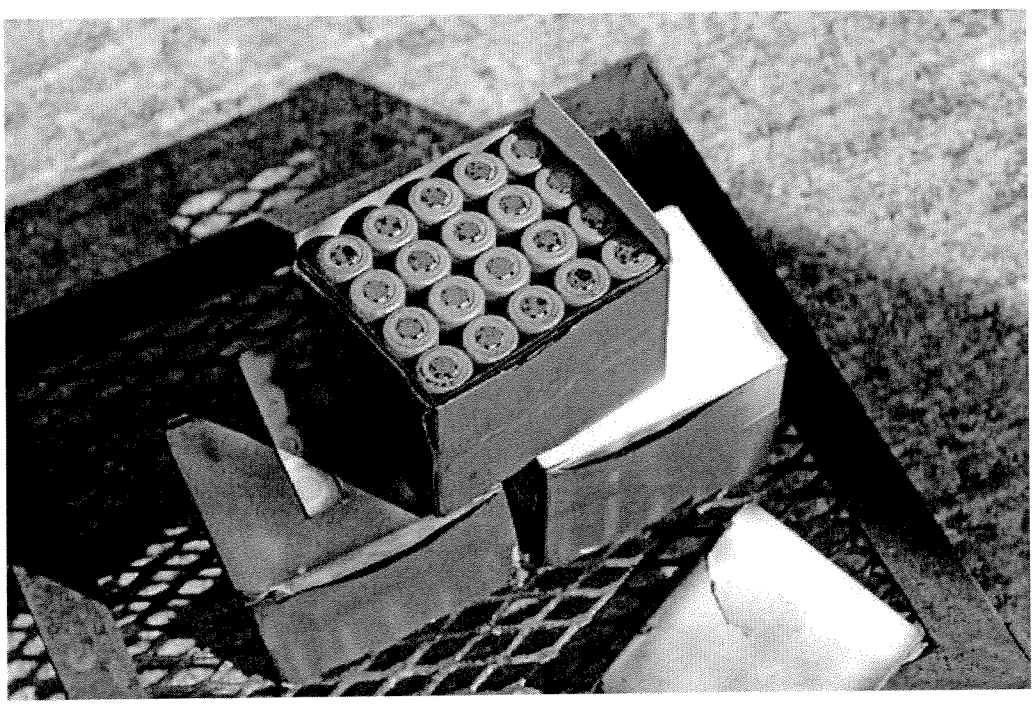

Figure C-11. Manufacturer A, 3 boxes with 20 cells each, 50% SOC, 11" pan.

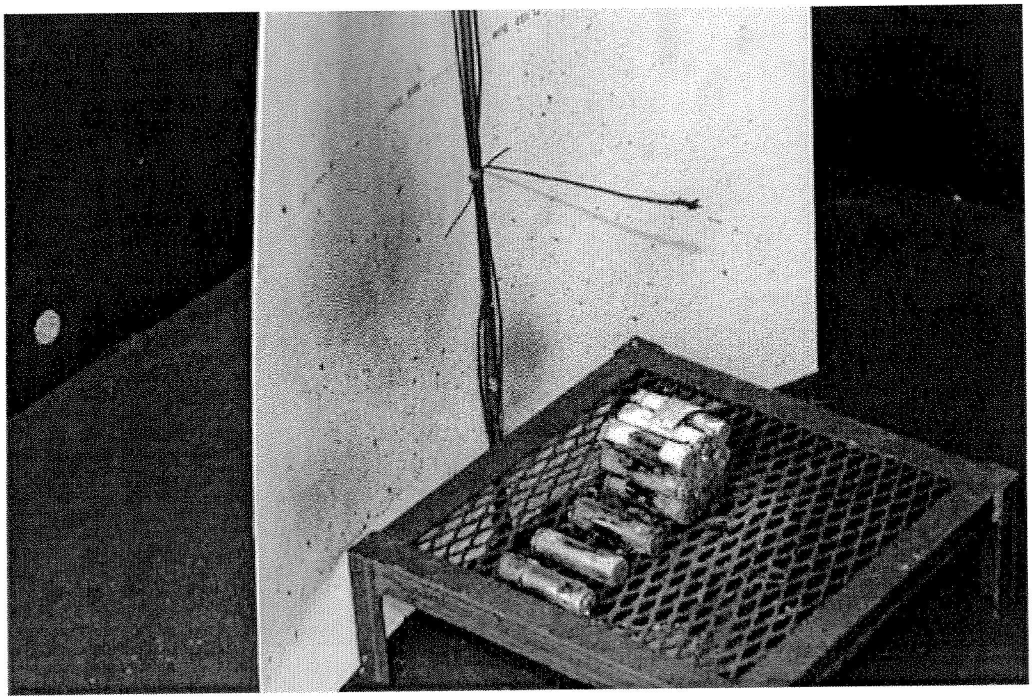

Figure C-12. Manufacturer A, 12 cells, 50% SOC, 5" pan, Cargo Liner A.

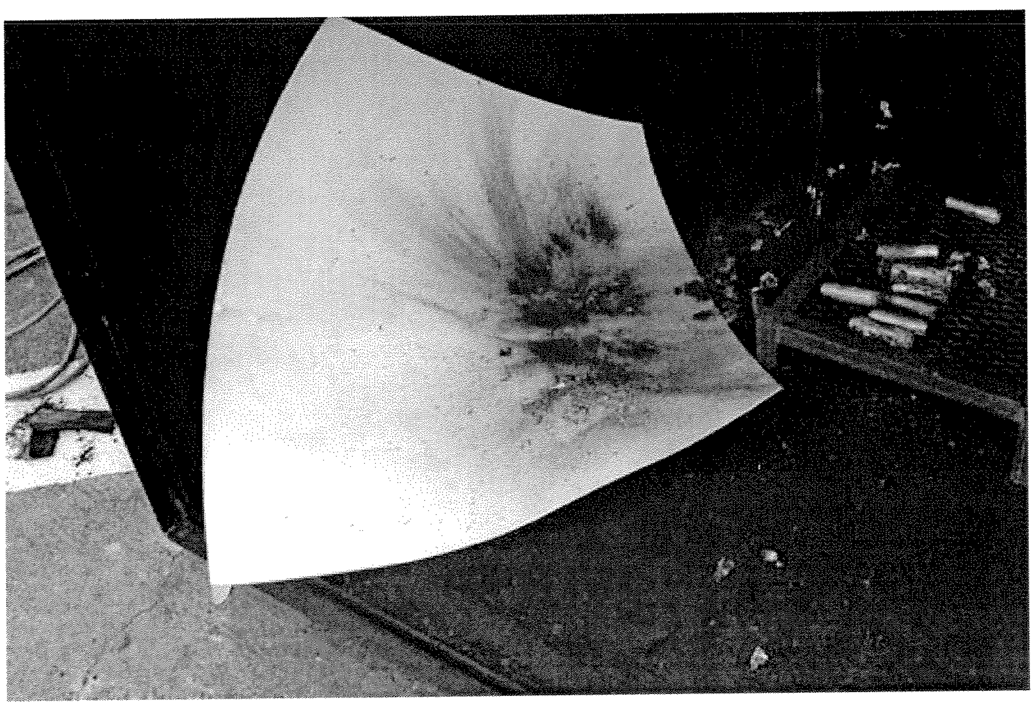

Figure C-13. Manufacturer A, 12 cells, 50% SOC, 5" pan, Cargo Liner B.

Figure C-14. Manufacturer A, 4 cells, 35% SOC, 5" pan, Halon 1301 applied after 2 cells vented.

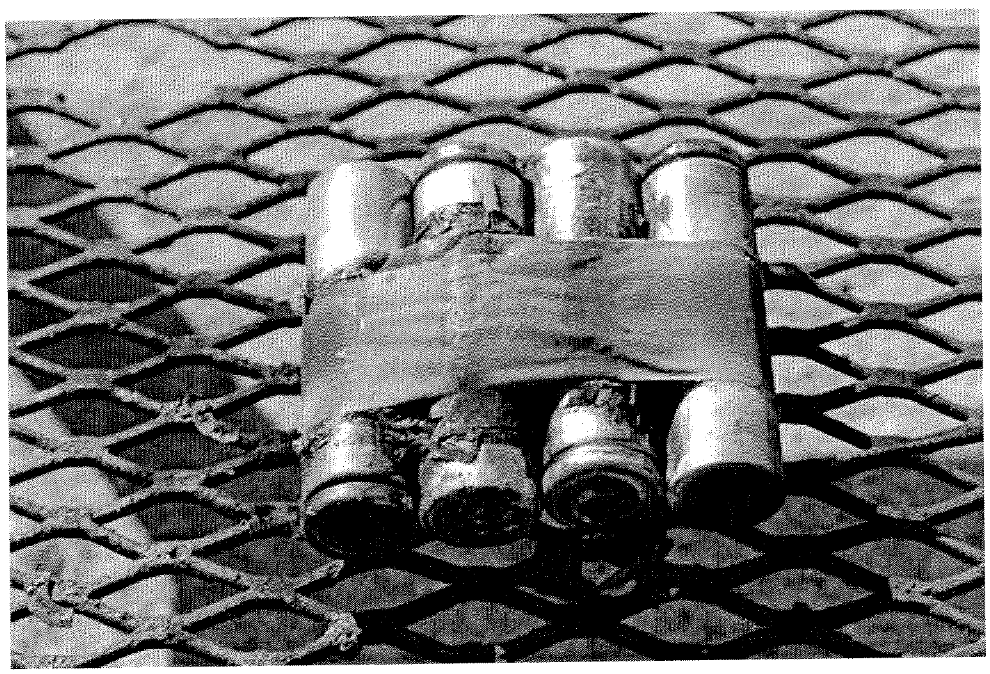

Figure C-15. Manufacturer A, 4 cells, 50% SOC, 5" pan, Halon 1301 applied after 2 cells vented.

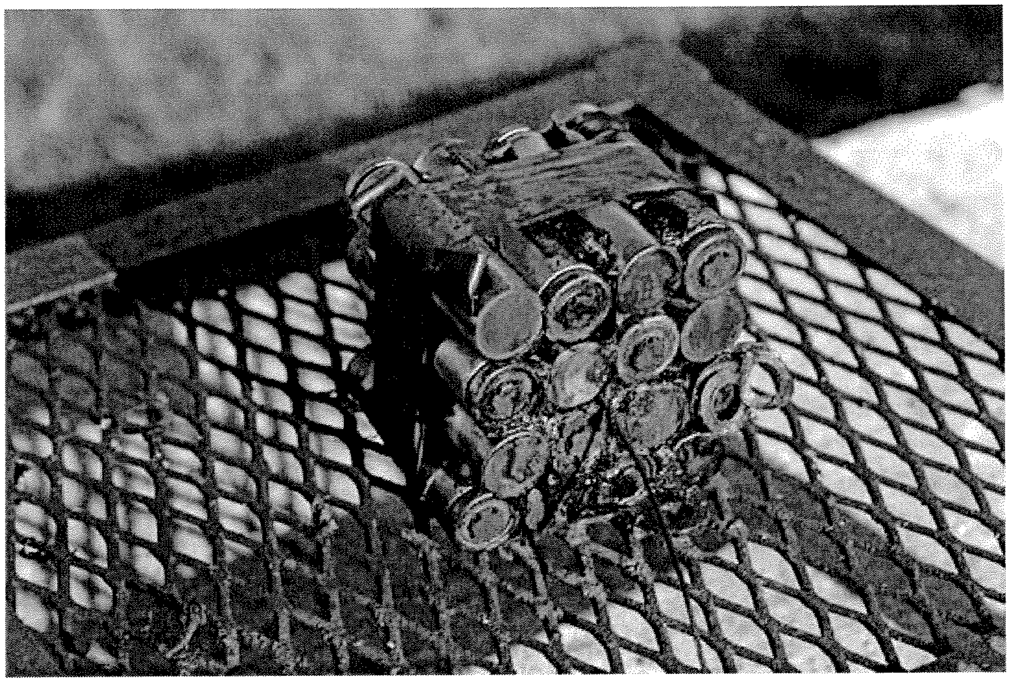

Figure C-16. Manufacturer A, 16 cells, 35% SOC, 5" pan, Halon 1301 applied after approximately 7 cells had vented.

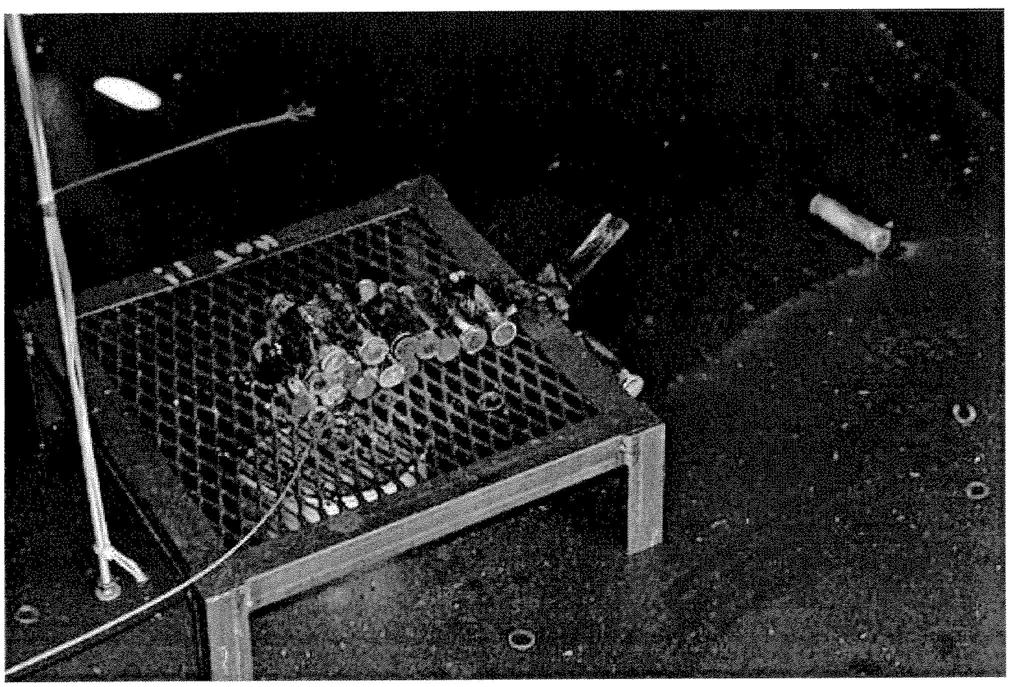

Figure C-17. Manufacturer A, 16 cells, 50% SOC, 5" pan, Halon 1301 applied after approximately 3 minutes.

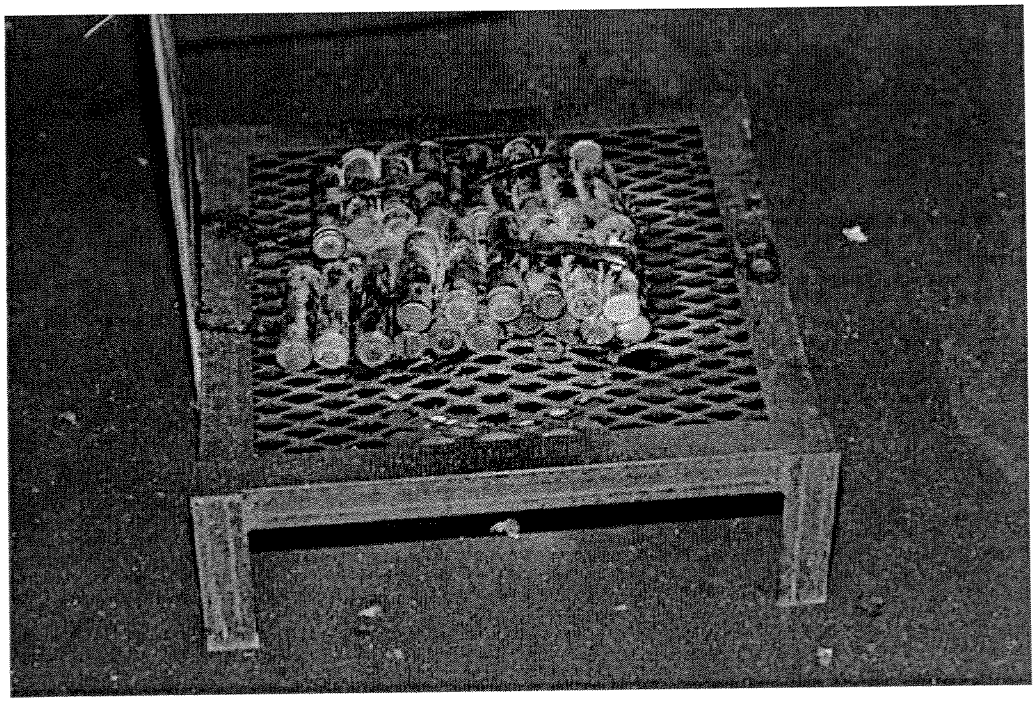

Figure C-18. Manufacturer A, 32 cells, 50% SOC, 5" pan, Halon 1301 applied at approximately 3 minutes (after cells began venting).

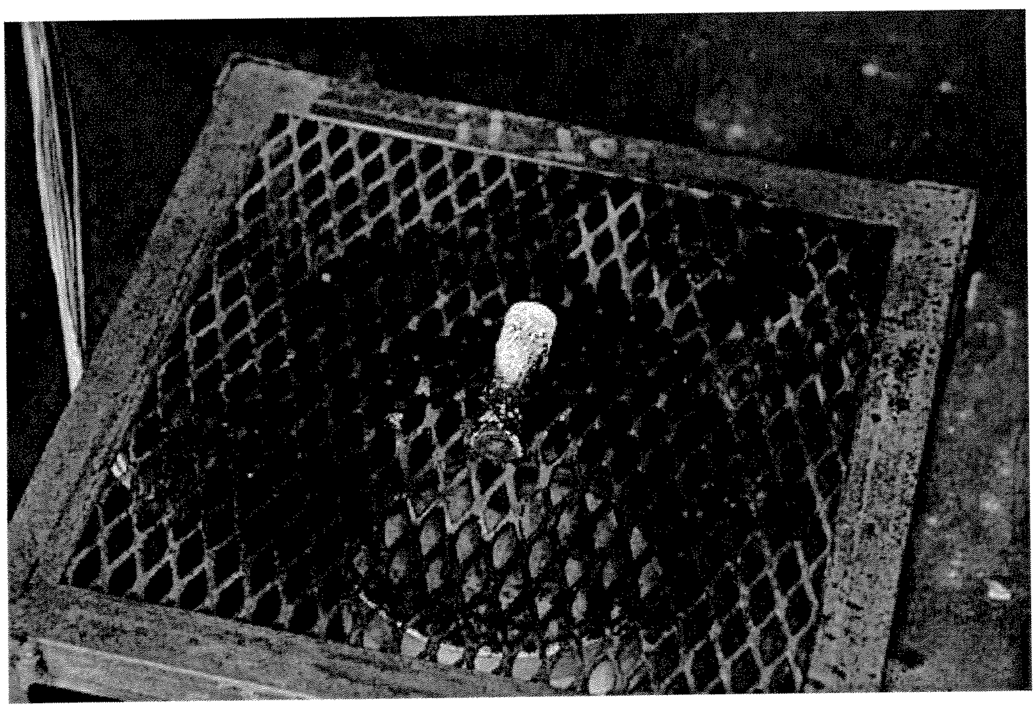

Figure C-19. Manufacturer B, single cell, 50% SOC, 5" pan.

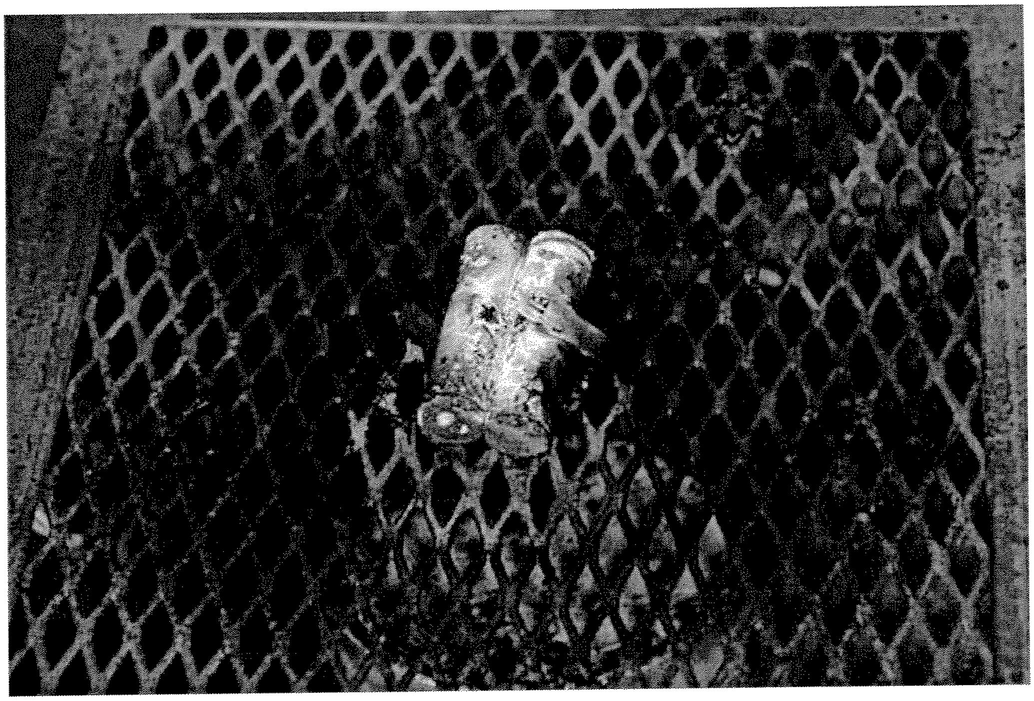

Figure C-20. Manufacturer B, 2 cells, 50% SOC, 5" pan.

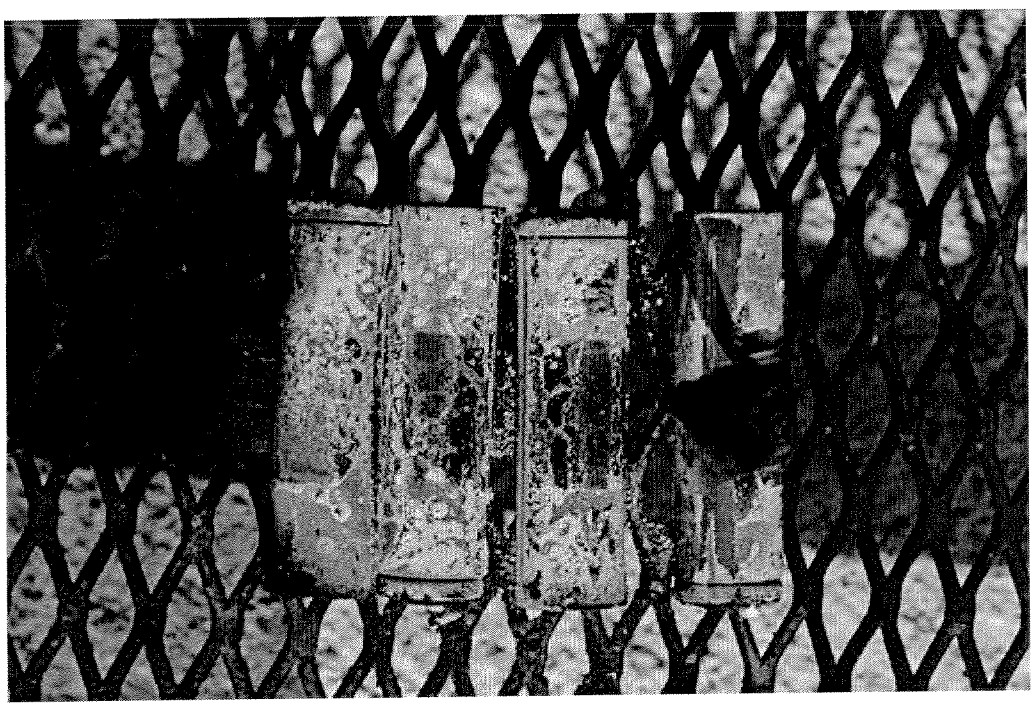

Figure C-21. Manufacturer B, 4 cells, 50% SOC, 5" pan.

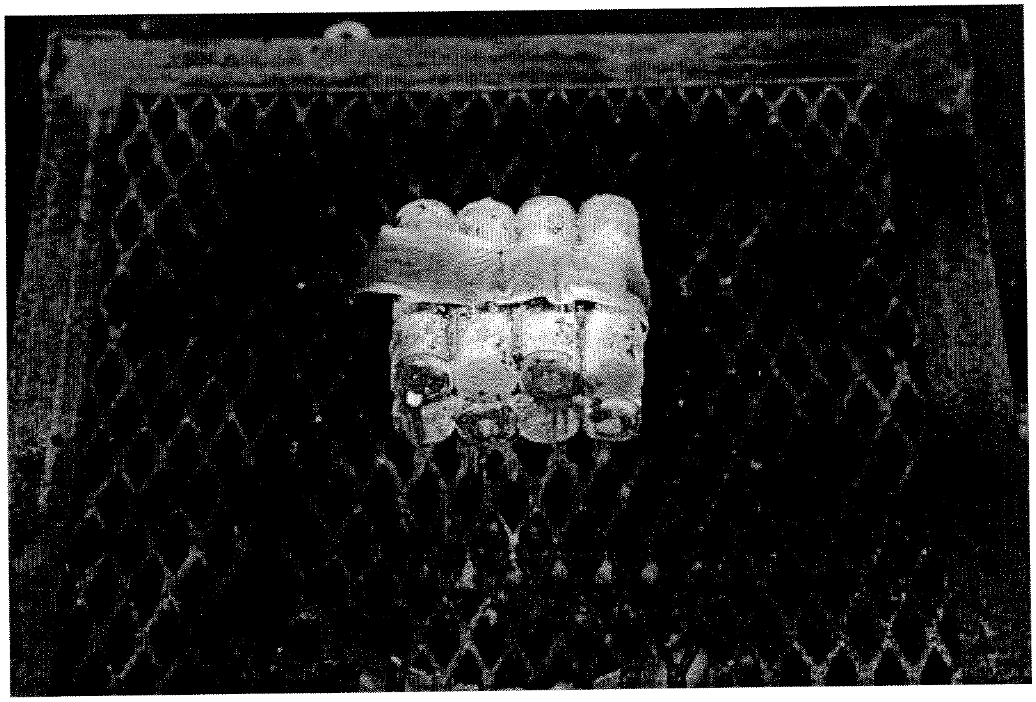

Figure C-22. Manufacturer B, 8 cells, 50% SOC, 5" pan.

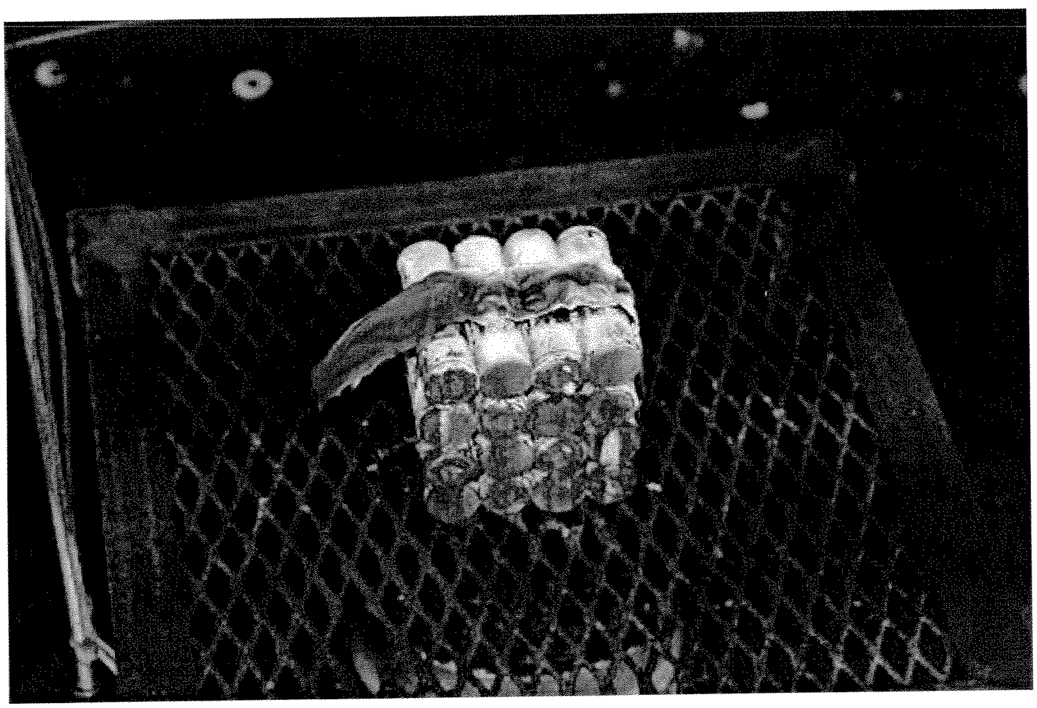

Figure C-23. Manufacturer B, 16 cells, 50% SOC, 5" pan.

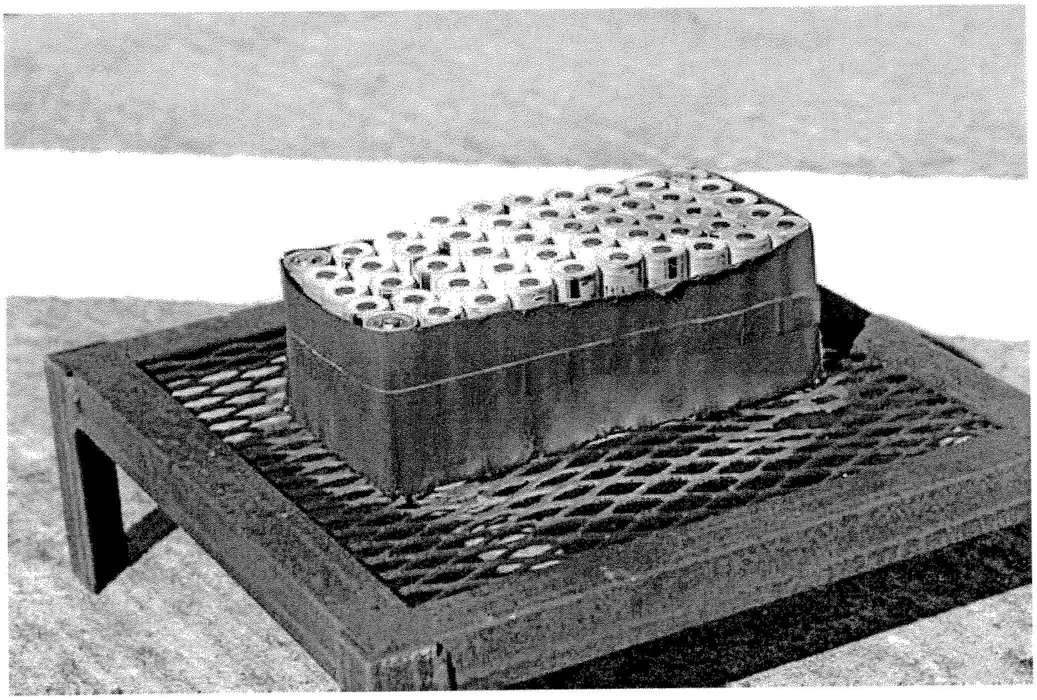

Figure C-24. Manufacturer B, 1 box with 50 cells, 50% SOC, 11" pan.

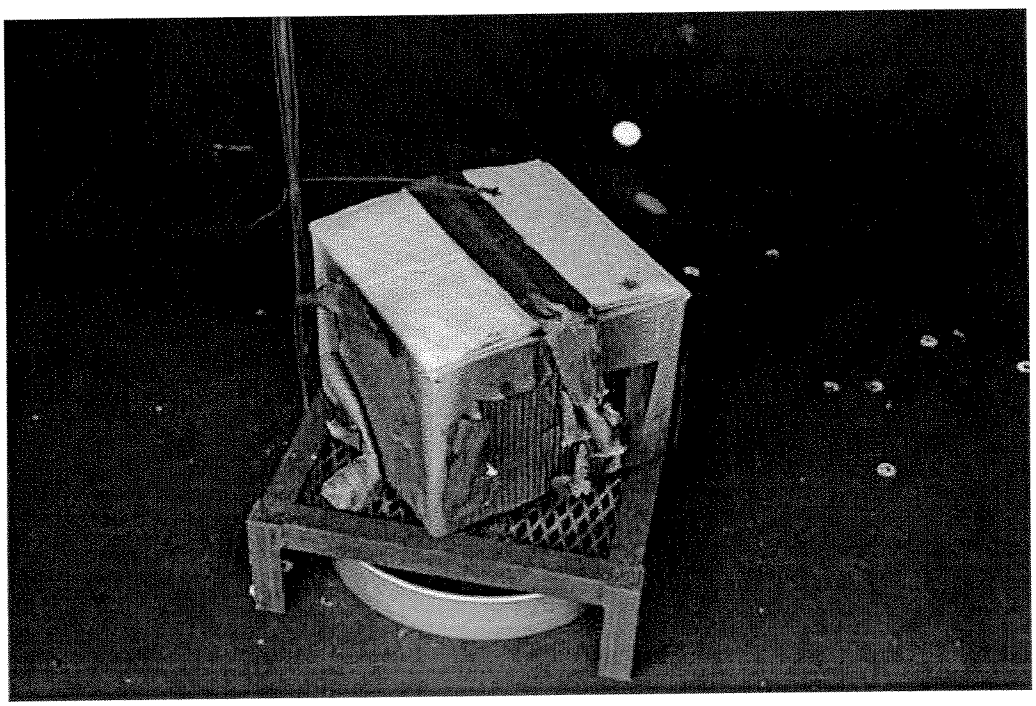

Figure C-25. Manufacturer B, 3 boxes of 50 cells each, 50% SOC, 11" pan.

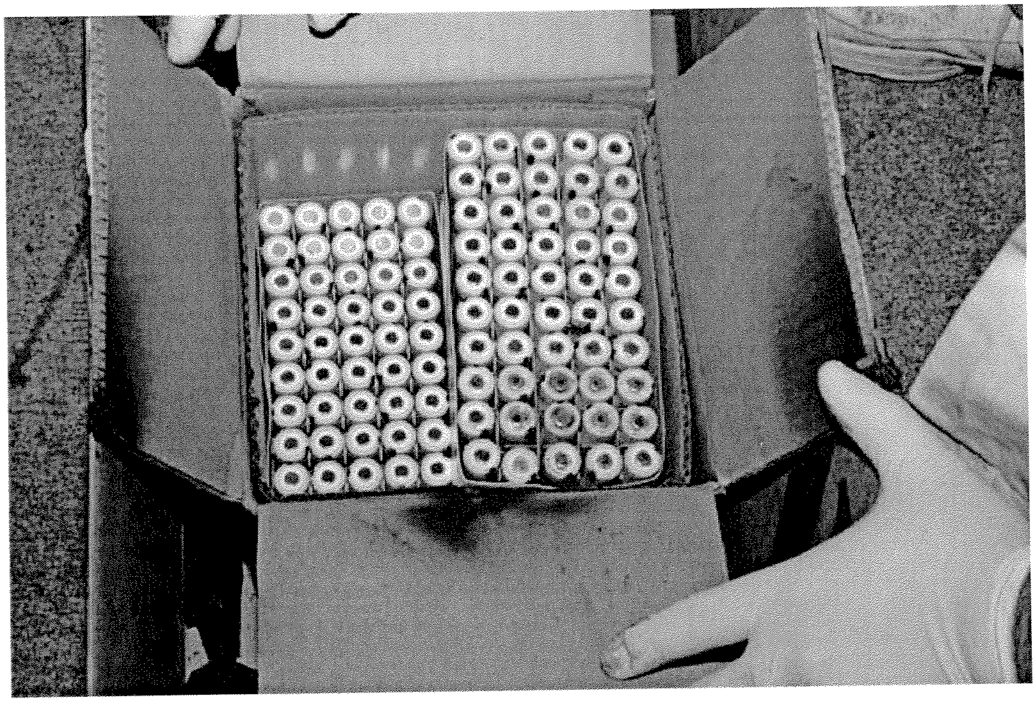

Figure C-26. Manufacturer B, 3 boxes of 50 cells each, 50% SOC, 11" pan.

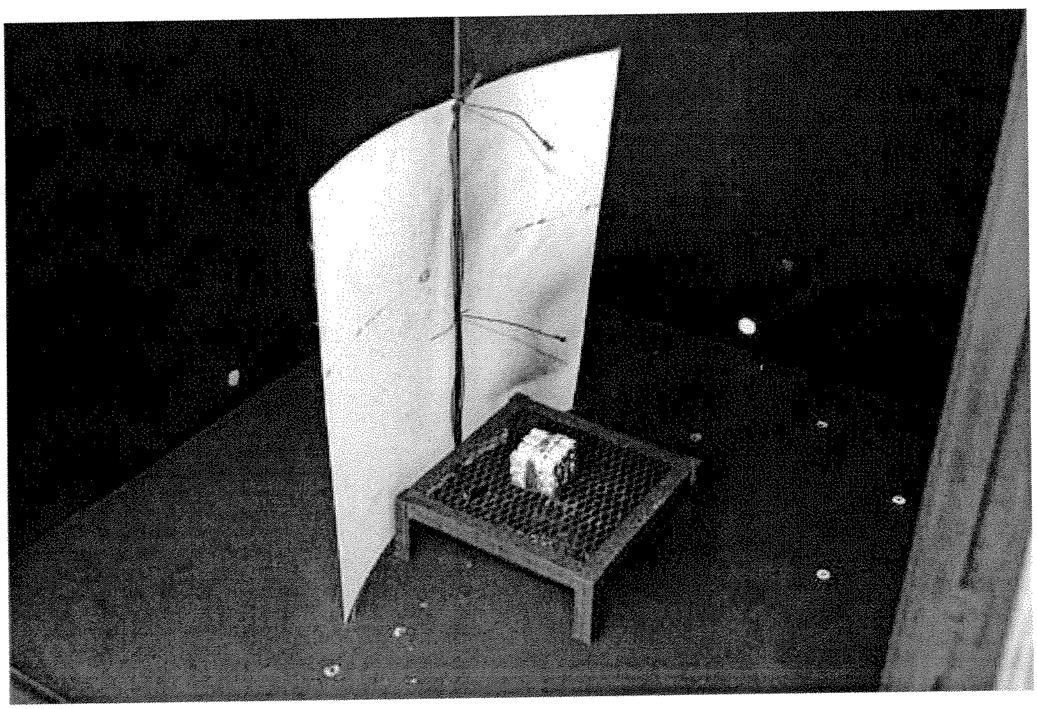

Figure C-27. Manufacturer B, 12 cells, 50% SOC, 5" pan, Cargo Liner A.

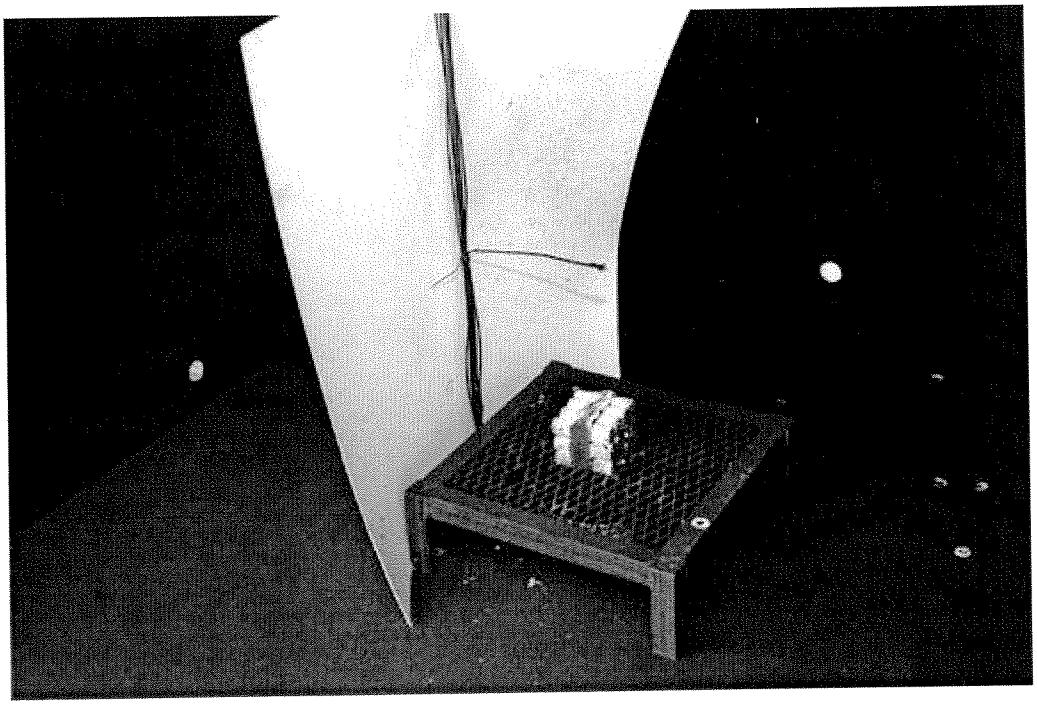

Figure C-28. Manufacturer B, 12 cells, 50% SOC, 5" pan, Cargo Liner B.

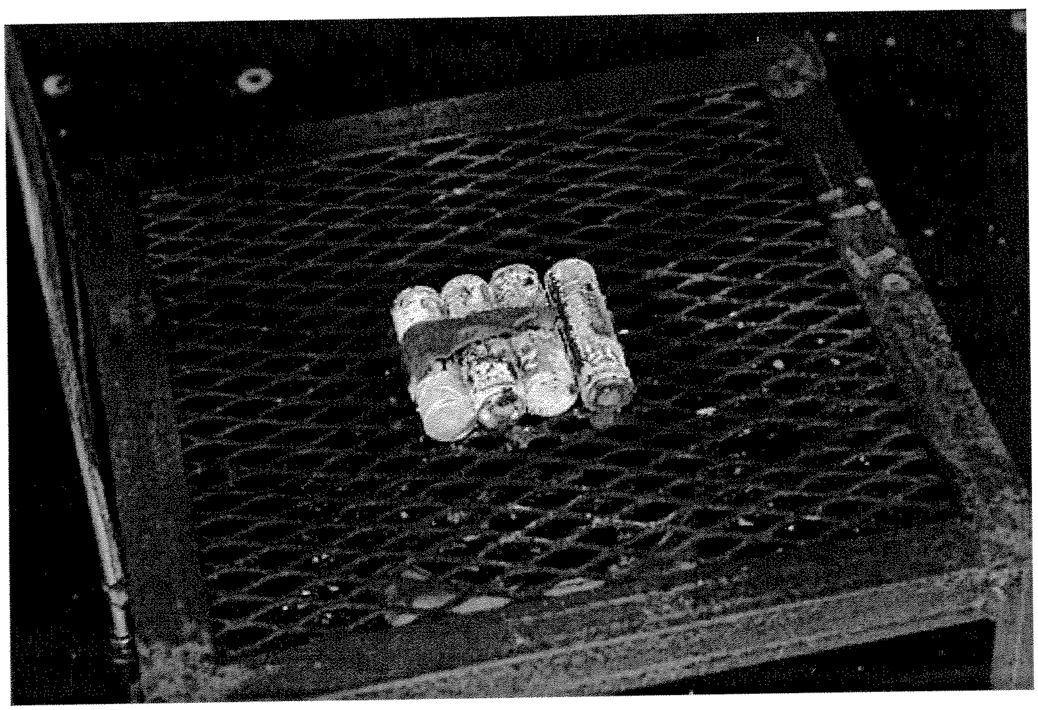

Figure C-29. Manufacturer B, 4 cells, 50% SOC, 5" pan, Halon 1301 applied after 2 cells vented.

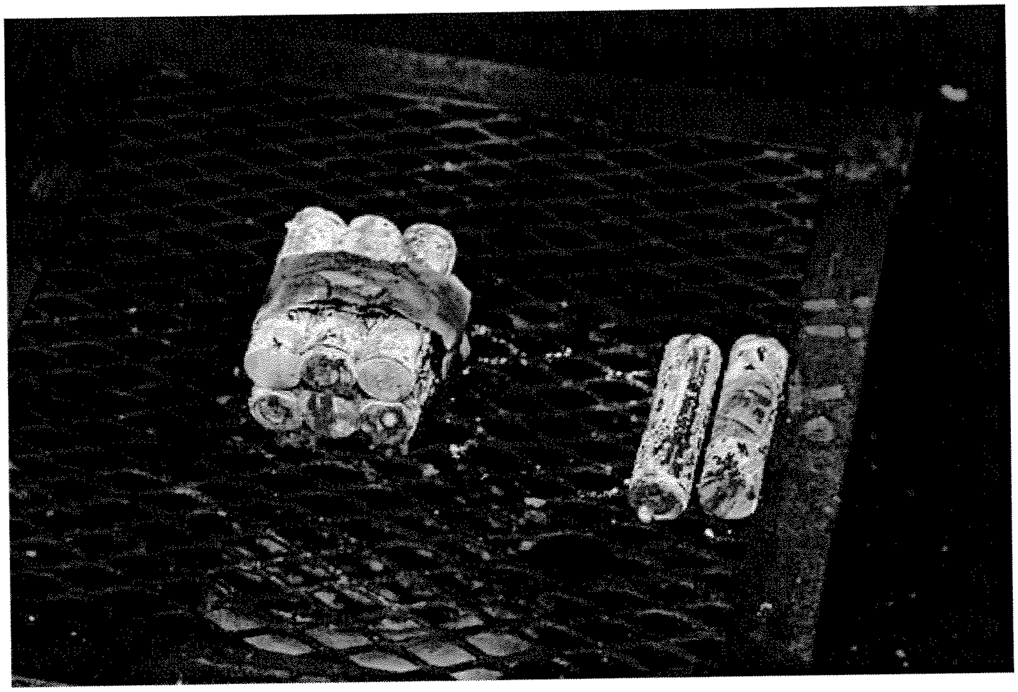

Figure C-30. Manufacturer B, 8 cells, 50% SOC, 5" pan, Halon 1301 applied after 4 cells vented.

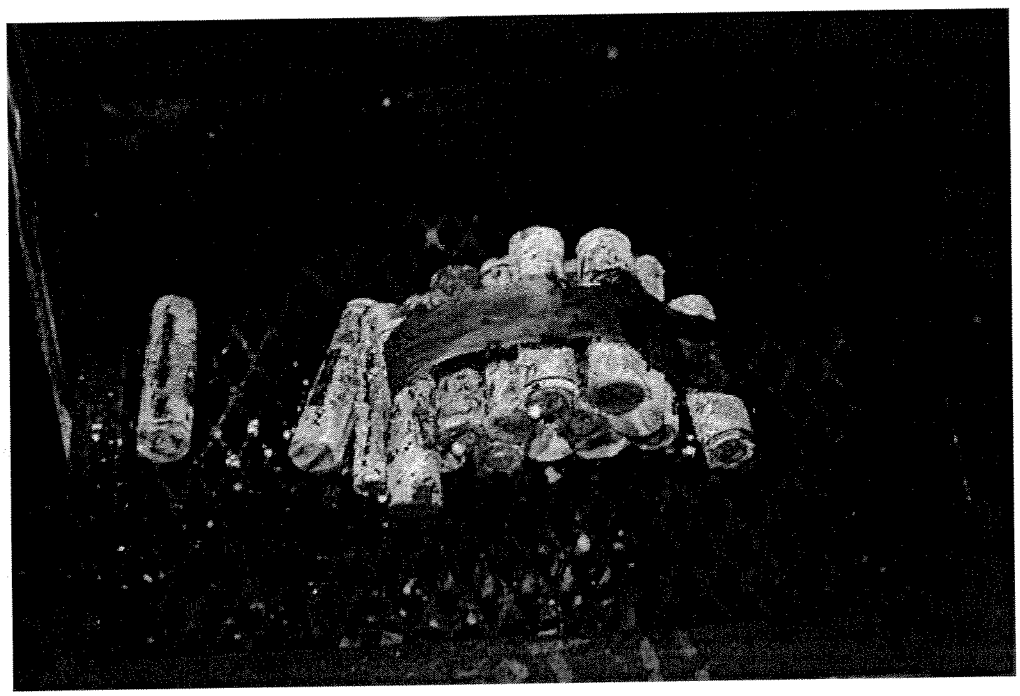

Figure C-31. Manufacturer B, 16 cells, 50% SOC, 5" pan, Halon 1301 applied after approximately 7 cells vented.

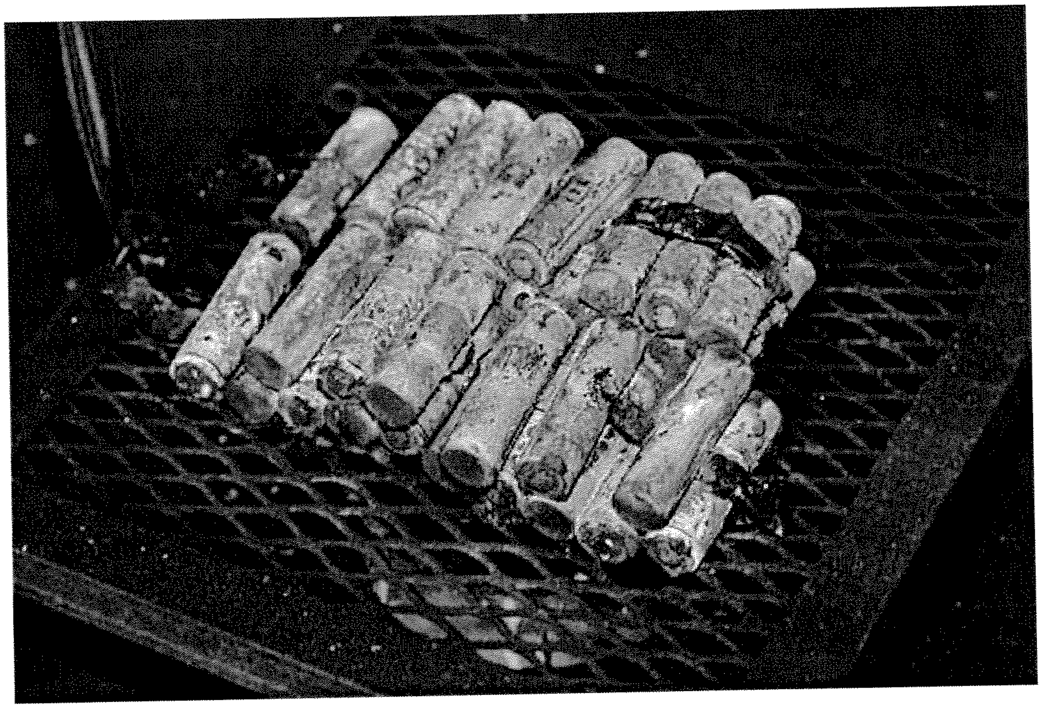

Figure C-32. Manufacturer B, 32 cells, 50% SOC, 5" pan, Halon 1301 applied after approximately 3 minutes (after cells began venting).

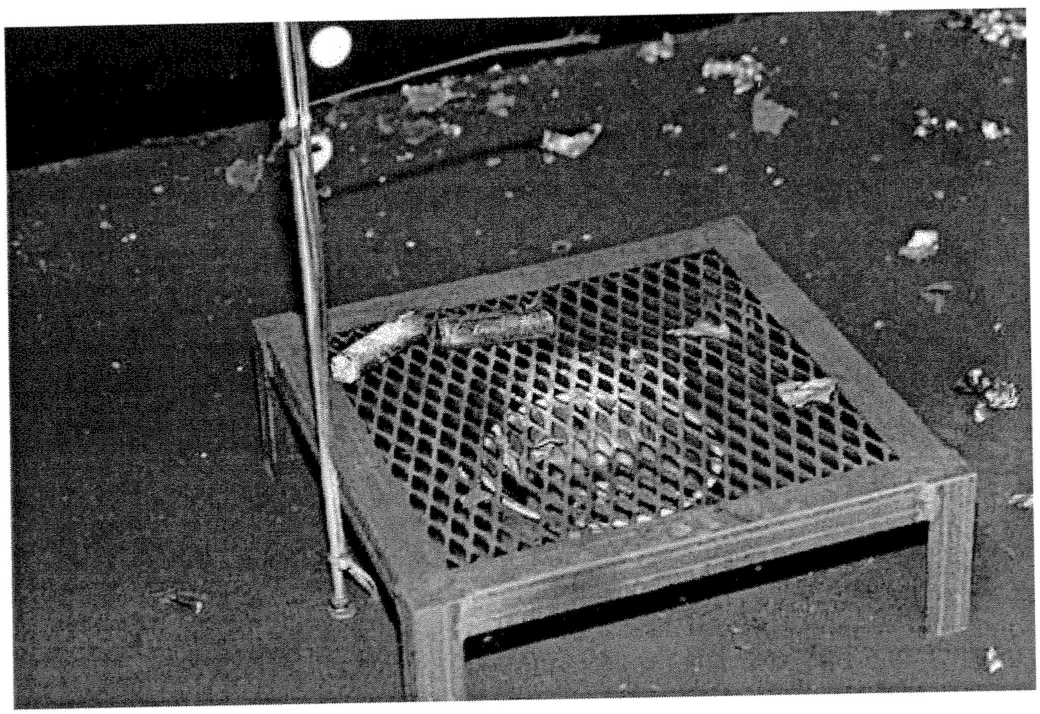

Figure C-33. Manufacturer C, 4 cells, 50% SOC, 5" pan (cell rupture and ejection of contents occurred).

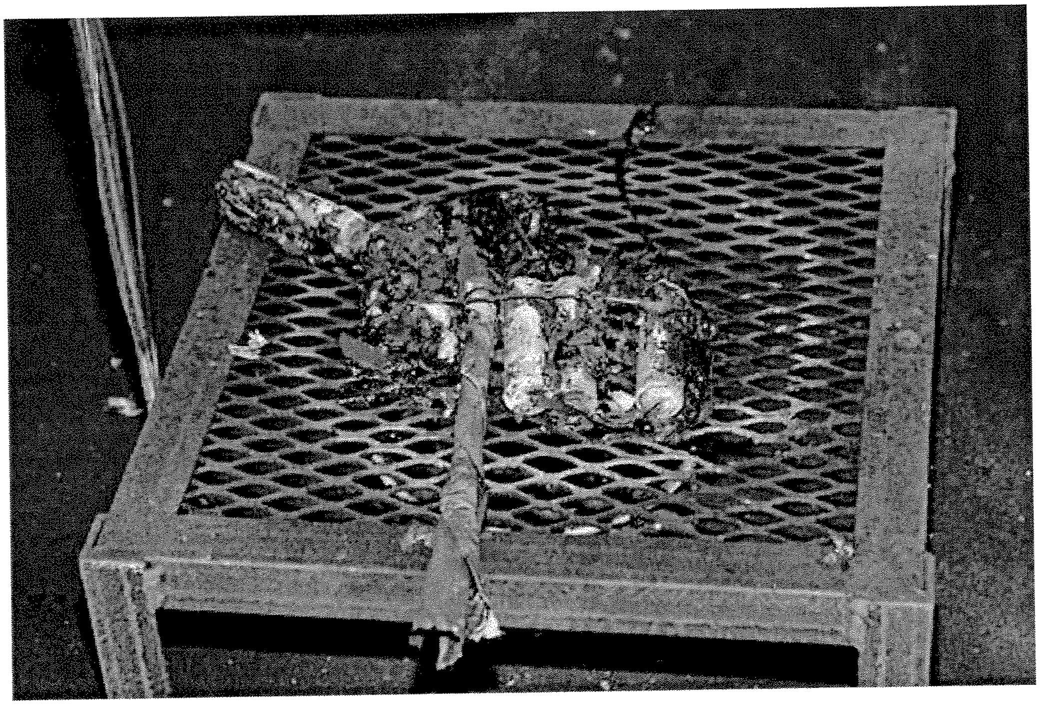

Figure C-34. Manufacturer C, one battery pack (8 cells), 50% SOC, 5" pan (cell rupture and ejection of contents occurred).

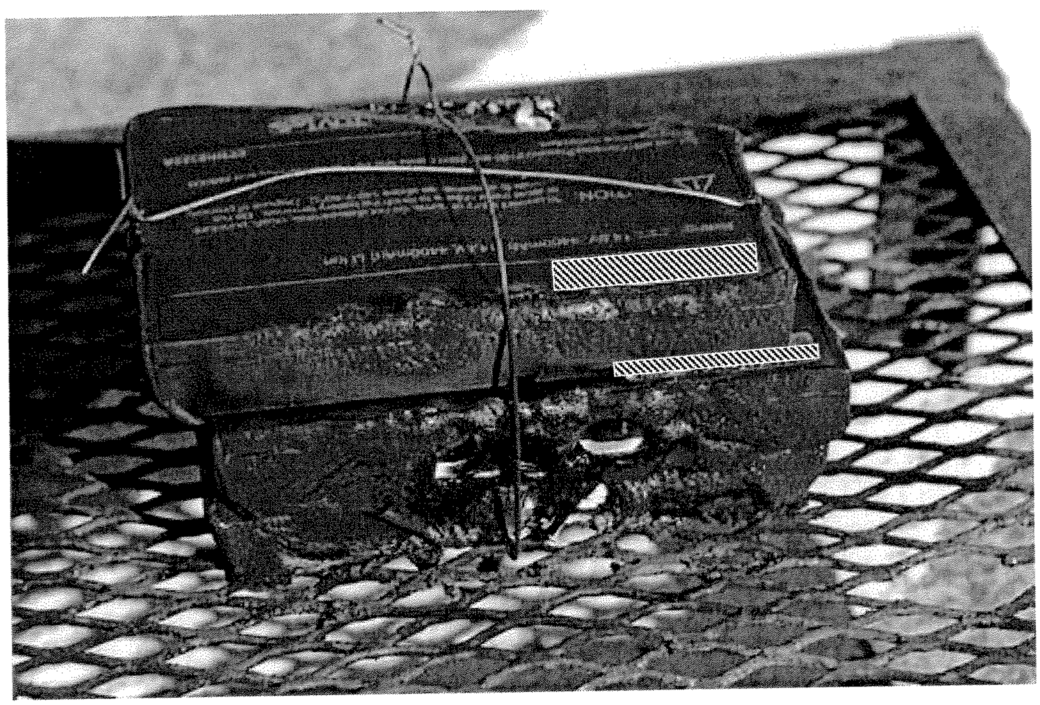

Figure C-35. Manufacturer C, 3 battery packs (8 cells each), 50% SOC, 11" pan.

Figure C-36. Manufacturer C, one battery pack (8 cells), 50% SOC, 5" pan, Cargo Liner A.

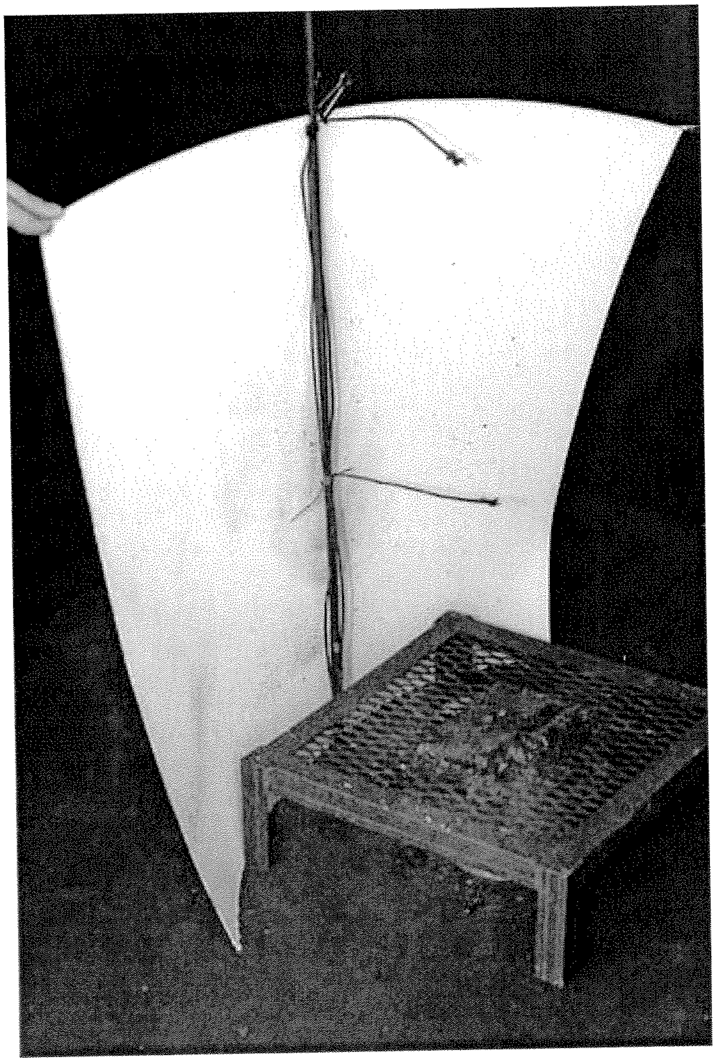

Figure C-37. Manufacturer C, one battery pack (8 cells), 50% SOC, 5" pan, Cargo Liner B.

Figure C-38. Manufacturer C, 4 cells, 50% SOC, 5" pan, Halon 1301 applied after 2 cells vented (cell rupture and ejection of contents occurred).

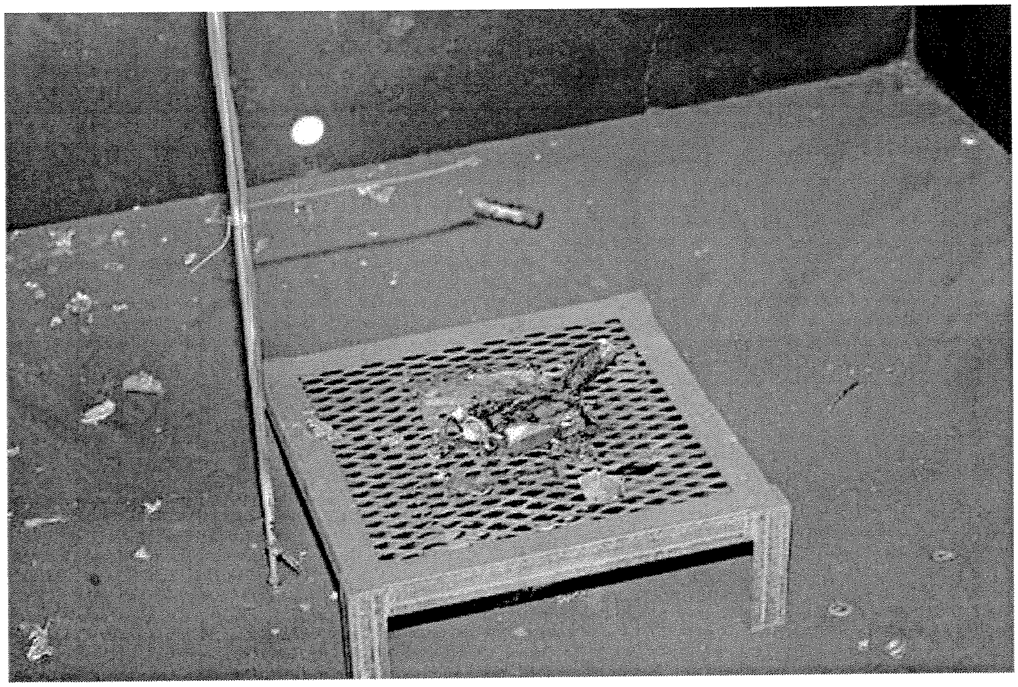

Figure C-39. Manufacturer C, one battery pack with 8 cells, 50% SOC, 5" pan, Halon 1301 applied after an observed cell venting (cell rupture and ejection of contents occurred).